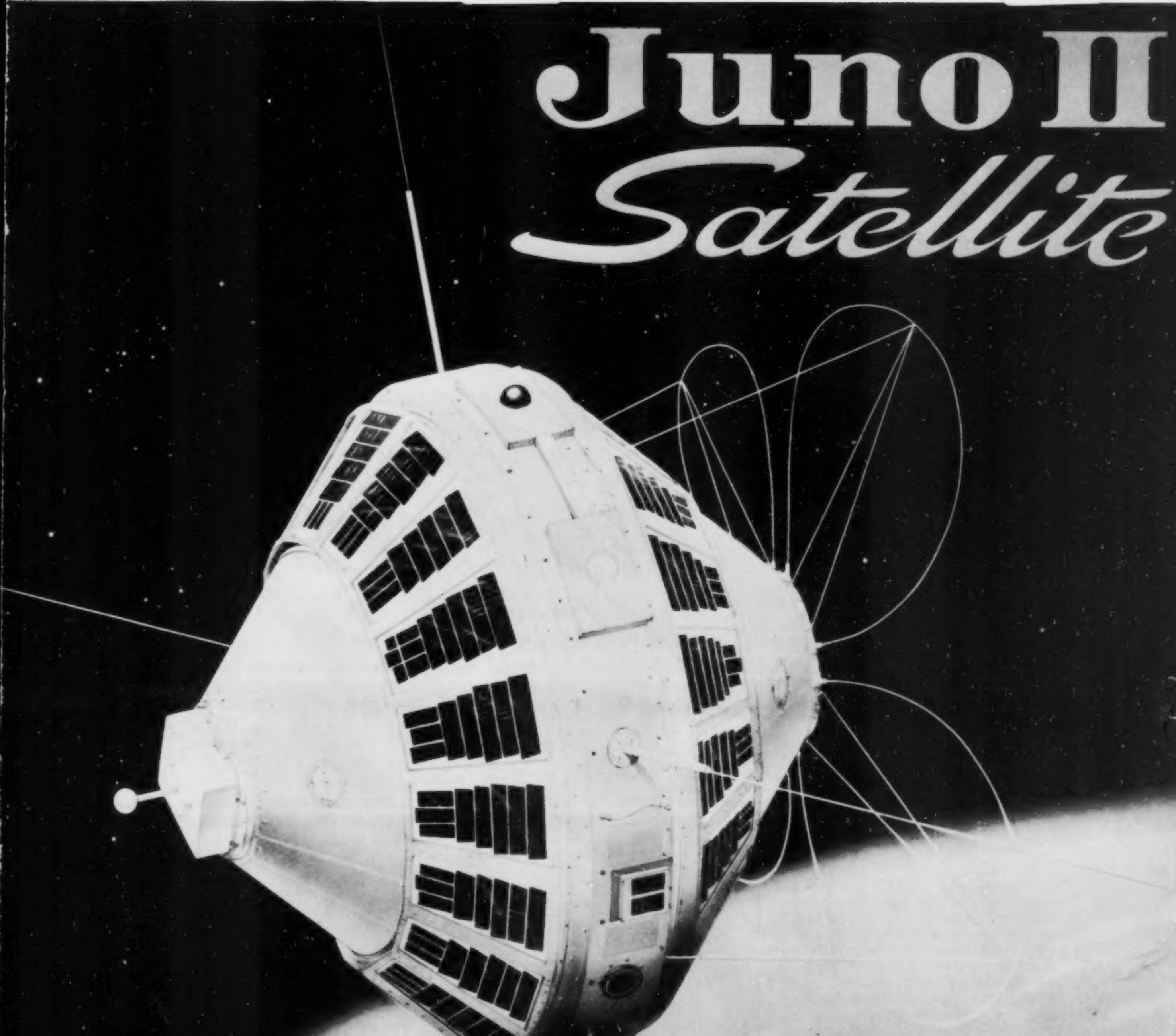
# SOLAR ENERGY

THE JOURNAL OF SOLAR ENERGY SCIENCE AND ENGINEERING

VOLUME IV 1960



THE ASSOCIATION FOR APPLIED SOLAR ENERGY

ARIZONA STATE UNIVERSITY
TEMPE, ARIZONA

# SOLAR ENERGY

THE JOURNAL OF SOLAR ENERGY SCIENCE AND ENGINEERING

VOLUME IV JANUARY, 1960 NUMBER 1

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THE JOURNAL OF SOLAR ENERGY SCIENCE AND ENGINEERING

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**Cover Photo: Picture by Joseph Muench**

Sunset Over the North Rim. Looking from Crazy Jug Point on the North Rim of the Grand Canyon into a brilliant sunset that illuminates the clouds. Grand Canyon Nat'l Park, Ariz.

# SOLAR ENERGY

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# *Some Solar Radiation Data Presentations For Use In Applied Solar Energy Programs By An International Group of Authors**

## Introduction

**By S. Fritz**

Chairman (1958–1959) of the Subcommission for Applied Solar Energy of the International Association of Meteorology and Atmospheric Physics

In 1956, the Radiation Commission of the International Association of Meteorology and Atmospheric Physics (IUGG) established a sub-commission on Applied Solar Energy (SASE). The terms of reference of the SASE were very broad, but in order to achieve some concrete results in one year, SASE set itself a specific task for the year 1958–1959. It has been obvious to the Radiation Commission for a long time that potential users of solar radiation data are not always aware of the existence of various types of solar radiation measurements. And moreover, the arrangement of the available data in the most usable form has been a problem to both radiation scientists and engineers. During 1958–1959 SASE therefore decided to assemble reports designed to display useful representations of solar radiation data. These reports were to serve as useful data sources themselves, and also to indicate avenues of approach to processing of additional data for use in applied solar energy projects.

This effort culminated in a session at the Radiation Symposium held in Oxford, England, in July 1959. Several of the reports presented in Oxford have been assembled and are presented below. These include:

(1) E. de Barry (West Germany); Examples of Statistical Representation of Radiation Data;

(2) S. Fritz and T. H. MacDonald (U.S.A.); The Number of days with Solar Radiation Above or Below Specific Values;

(3) H. Hinzpeter (East Germany); Frequency Distribution of Hourly Sums of Direct Solar Radiation at Potsdam;

(4) K. J. Kondratyev and M. P. Manolova (U.S.S.R.); The Radiation Balance of Slopes.

A fifth paper by R. Dogniaux (Belgium) dealt with diffuse sky radiation on a horizontal surface and the duration of sunshine as measured with a Campbell-Stokes "heliograph".

Scientists and engineers who are concerned with the application of solar energy to practical problems, will find in these papers a limited source of data. However, the organization of the data in these papers, either by theoretical or statistical means, may also suggest relations which may be of value in studying data from other places than those treated here.

At the conclusion of the session at which these papers were presented, W. Mörikofer,† of Davos, Switzerland, was elected the new Chairman of SASE.

* The editing of this series of contributions was undertaken by A. J. Drummond, Eppley Laboratory, who is also responsible for such translation as was necessary.

† Succeeded in January 1960 by A. J. Drummond (Newport, Rhode Island).

# Examples of Statistical Representation of Radiation Data

**By E. de Barry**

Mainz, West Germany

The material summarized in this paper is intended to illustrate how records of the total radiation from sun and sky, received on a horizontal surface, may be presented in order to make available data which are essential for users of solar energy. The tables and diagrams should therefore only be considered in this sense. The method of representation rather than numerical values is important here.* The author is convinced that many meteorological institutes and services will be prepared to evaluate radiation records in this or in a similar way if a demand for such data from producers and users of solar heating machines materializes.

Figs. 1 and 2, as well as Tables I and II, are based on records maintained at Lisbon, Portugal (Lat. 38° 43′ N, Lon. 9° 9′ W, height 77m) during the years 1947–1956[1]. Figs. 3 and 4 provide an example of the intercomparison of several stations; in this instance, the relevant data have been published by the Working Group for Radiation of Regional Association I of the World Meteorological Organization[2].

Fig. 1 shows the diurnal and annual variations of the total radiation in the usual form of isopleths. The diurnal variation for a particular month can be read off by following a horizontal line and the annual variation for a specific hour by following a vertical line, in the diagram.

Table I contains, for each calendar month at Lisbon, the absolute daily maximum and minimum of total radiation, the average maximum and minimum for the 10 years and the general means of the whole series of records.

Fig. 2 shows the frequency distribution, expressed in per cent (in a probability diagram), of the daily summations of the total radiation for each month. For example, in May 20 per cent of all daily values are lower than 500 cal/cm²/d, 50 per cent are lower or higher than 680 and 5 per cent are higher than 830 cal/cm²/d.

Figs. 3 and 4 should be interpreted in the same way. Table II, which represents an analysis of the Lisbon data, needs somewhat more explanation. The month of October may be chosen as an example. The upper part of this table gives the number of sequences of $n$ days during which certain specific values were not attained. The first number 1 in the row marked (100) means that in nine years in one case only ($n = 1$) a

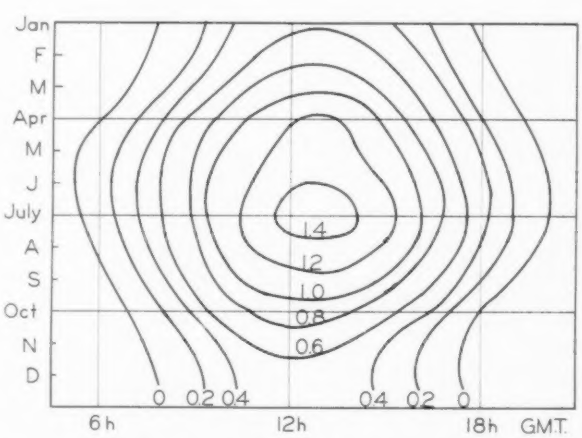


FIG. 1—Isopleths of the diurnal and annual variations of total sun and sky radiation (cal/cm²/min), received on a horizontal surface at Lisbon (Lat. 38° 43′ N, Lon. 9° 9′ W, h 77m); 1947–1955.

value smaller than 100 cal/cm²/d was observed, i.e., that the absolute minimum is lower than 100 (Fig. 2). Line 2 shows the number of cases in which the total radiation was between 100 and 200 cal/cm²/d. On 14 single days, twice on two consecutive days and once on three consecutive days, daily figures between these threshold values have been observed. Line 5 demonstrates that, during the nine years of record, all the daily totals ($n = 31$) were lower than 500 cal/cm²/d in six years, and in the three remaining years were lower than 600; i.e., the value of 500 was exceeded

* It is possible that the Lisbon data are somewhat high because values of 900 cal/cm²/d are very seldom experienced even in similar climatic situations. The author cannot verify the accuracy of the data.

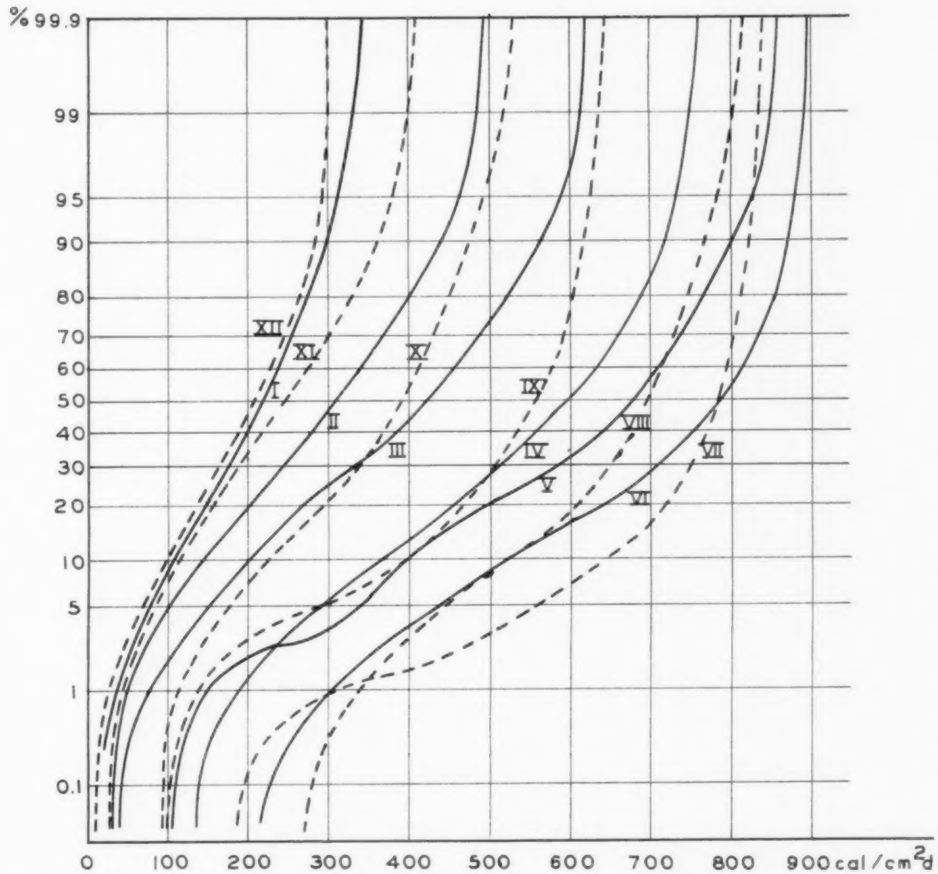


FIG. 2—Frequency distribution (percentage) of the daily summations of total radiation, for each calendar month, at Lisbon; 1947–1956.

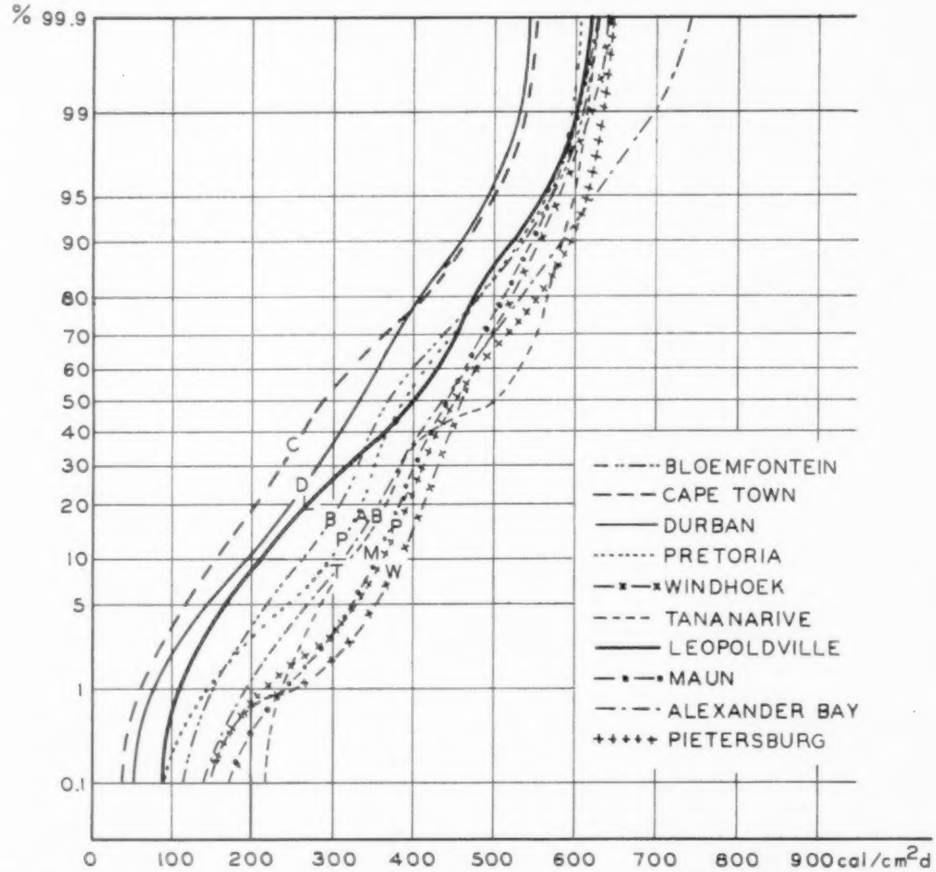


FIG. 3—Frequency distribution (percentage) of the daily summations of total radiation at specified African stations, April–September, 1954–1955.

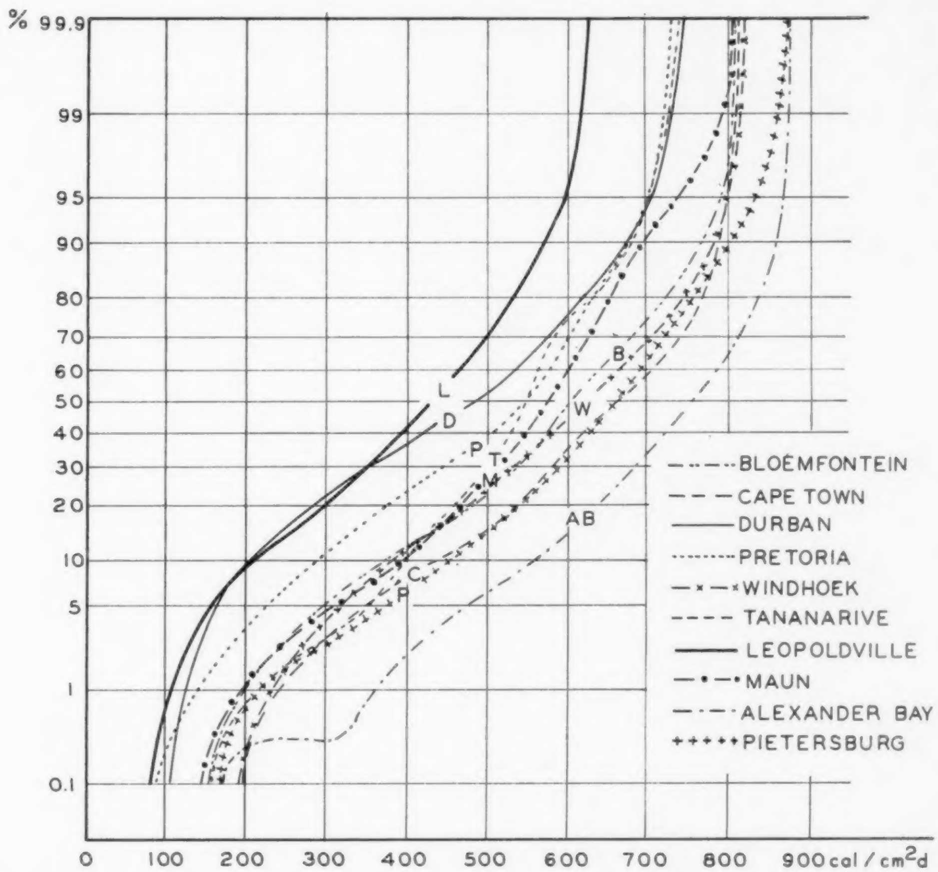


FIG. 4—Frequency distribution (percentage) of the daily summations of total radiation at specified African stations; October–March, 1954–1955.

occasionally; how often this occurred may be determined from the lower portion of the table.

This lower portion gives the number of periods of specific duration when the daily totals were higher than the indicated threshold values. Thus, it is apparent that the lowest value for the month ($n = 31$) was between 0 and 100 cal/cm²/d in one year (as already mentioned), above 100 but not above 200 in seven of the years and between 200 and 300 cal/cm²/d in the remaining years of the series. When we look at the last line we see that the value of 500 cal/cm²/d was exceeded in one case on a single day; in two cases the amount of total radiation exceeded the same value on three consecutive days. This corresponds to our above-mentioned finding that in three years all the 31 days had radiation values which were below 600 but not below 500 cal/cm²/d.

## REFERENCES


1. Anais do Inst. Geofisico do Infante D. Luis, 1947–1956, Lisbon.
2. Quarterly Radiation Bulletin, Weather Bureau, Pretoria, Union of South Africa, 1954 and 1955.


TABLE I—Monthly values of the absolute maximum and minimum, the average maximum and minimum and the mean radiation (cal/cm²/d) at Lisbon; 1947–1956

| | Absolute Maximum | Average Maximum | Absolute Minimum | Average Minimum | Long-period Mean |
|---|---|---|---|---|---|
| January | 372.2 | 330.7 | 19.1 | 56.7 | 212.2 |
| February | 487.7 | 454.0 | 47.0 | 84.3 | 301.3 |
| March | 643.4 | 591.1 | 55.4 | 120.9 | 405.3 |
| April | 776.6 | 705.7 | 160.6 | 226.7 | 567.3 |
| May | 846.7 | 818.5 | 110.9 | 224.0 | 637.3 |
| June | 904.0 | 863.3 | 246.4 | 385.0 | 734.9 |
| July | 872.0 | 846.7 | 225.8 | 431.2 | 756.3 |
| August | 829.0 | 794.6 | 277.0 | 379.7 | 665.4 |
| September | 681.1 | 658.4 | 103.1 | 236.3 | 522.4 |
| October | 544.1 | 501.4 | 69.1 | 136.1 | 367.9 |
| November | 421.4 | 374.0 | 35.1 | 65.0 | 239.4 |
| December | 289.4 | 277.1 | 24.7 | 44.3 | 192.0 |

TABLE II—Frequency of periods of $n$ consecutive days with daily summations of total radiation (cal/cm²) below and above fixed threshold values at Lisbon; 1947–1956

January (9 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <100 | 17 | 4 | | | | | | | | | | | |
| <200 | 20 | 11 | 9 | 1 | 3 | 1 | | 1 | | | 1 | | |
| <300 | 1 | 2 | | 3 | | 2 | 1 | 1 | 1 | 1 | 6 | 2 | 1 |
| <400 | | | | | | | | | | | | | 8 |
| >0 | | | | | | | | | | | | | 8 |
| >100 | 1 | 6 | 1 | 3 | 6 | 2 | 1 | | | 1 | 5 | 2 | 1 |
| >200 | 19 | 8 | 9 | 3 | 3 | 2 | 2 | 1 | 2 | 1 | 1 | | |
| >300 | 11 | 3 | | 1 | | | | | | | | | |

TABLE II—(Continued)

February (10 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–27/28 | 28/29 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <100 | 10 | 2 | | | | | | | | | | | |
| <200 | 22 | 8 | 2 | 3 | 1 | | | | | | | | |
| <300 | 15 | 12 | 4 | 4 | 1 | 3 | 1 | 1 | | | 2 | | |
| <400 | 8 | 1 | | 3 | | 3 | 2 | 2 | | 2 | 4 | 2 | 1 |
| <500 | | | | | | | | | | | | | 9 |
| >0 | | | | | | | | | | | | | 7 |
| >100 | 4 | 1 | 2 | 2 | 1 | | 1 | 2 | | | 2 | 4 | 3 |
| >200 | 14 | 6 | 7 | 4 | 1 | 3 | 2 | 2 | | 1 | 5 | 3 | |
| >300 | 22 | 9 | 2 | 1 | 2 | 6 | | 1 | | | 2 | | |
| >400 | 9 | 7 | 1 | 3 | | | 2 | | | | | | |

March (10 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <100 | 4 | 1 | | | | | | | | | | | |
| <200 | 18 | 3 | | 1 | | | | | | | | | |
| <300 | 33 | 11 | 2 | 2 | 1 | | | | | | | | |
| <400 | 19 | 13 | 7 | 4 | 3 | | 1 | 1 | | | | | |
| <500 | 16 | 7 | 7 | 4 | 2 | | 2 | | 3 | 2 | 8 | 1 | |
| <600 | | 2 | | 2 | | | | | | | 1 | 3 | 5 |
| <700 | | | | | | | | | | | | | 5 |
| >100 | | 1 | | 1 | 1 | | | | | 1 | 3 | 3 | 5 |
| >200 | 3 | 4 | 1 | 3 | 2 | | 3 | 3 | 2 | 2 | 4 | 1 | 2 |
| >300 | 13 | 15 | 5 | 4 | 2 | 1 | 3 | 2 | 1 | 4 | 4 | | |
| >400 | 23 | 17 | 5 | 1 | 4 | 6 | 2 | 2 | | | 3 | | |
| >500 | 20 | 6 | 1 | 1 | 1 | | 1 | 1 | | 1 | | | |
| >600 | 4 | 2 | 1 | | | | | | | | | | |

April (10 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <200 | 4 | | | | | | | | | | | | |
| <300 | 13 | 3 | | | | | | | | | | | |
| <400 | 23 | 3 | 3 | 1 | | | | | | | | | |
| <500 | 29 | 13 | 4 | 1 | | | 1 | | | | | | |
| <600 | 21 | 10 | 11 | 4 | 1 | 3 | 1 | 1 | | 1 | 1 | | |
| <700 | 5 | 2 | 1 | 1 | | 1 | 1 | | 2 | 1 | 8 | 2 | 1 |
| <800 | | | | | | | | | | | | | 9 |
| >100 | | | | | | | | | | | | | 3 |
| >200 | | | 1 | | 1 | | | | | | 4 | 1 | 6 |
| >300 | | 2 | 2 | 3 | 1 | 3 | | 1 | | | 10 | 2 | 1 |
| >400 | 1 | 8 | 3 | 4 | 5 | 2 | | 2 | 2 | 1 | 8 | 1 | |
| >500 | 17 | 9 | 6 | 5 | 3 | 2 | 2 | 2 | 1 | | 4 | 1 | |
| >600 | 24 | 16 | 7 | 2 | 2 | 1 | 1 | | | | 4 | | |
| >700 | 5 | 6 | 1 | | 2 | | | 1 | | | | | |

May (10 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <200 | 8 | 1 | | | | | | | | | | | |
| <300 | 9 | 2 | | | | | | | | | | | |
| <400 | 21 | 3 | 3 | | | | | | | | | | |
| <500 | 29 | 9 | 2 | 2 | 1 | | | | | | | | |
| <600 | 27 | 17 | 8 | 2 | 2 | | 1 | 1 | | | | | |
| <700 | 20 | 9 | 8 | 3 | 3 | 4 | 1 | 1 | | | 3 | | |
| <800 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 4 | 3 | 2 |
| <900 | | | | | | | | | | | | | 8 |
| >100 | | | | | | | | | | | | | 6 |
| >200 | | 1 | | 1 | 1 | | 1 | | | | 7 | 2 | 1 |
| >300 | | 1 | 1 | 1 | 1 | | 1 | | | | 8 | 2 | 3 |
| >400 | 3 | 2 | 4 | 2 | 4 | 1 | 2 | 2 | 1 | | 7 | 3 | |
| >500 | 14 | 6 | 7 | 2 | 3 | 1 | 3 | 1 | 3 | 1 | 5 | 1 | |
| >600 | 22 | 7 | 7 | 7 | 5 | 2 | | | 2 | 1 | 2 | 1 | |
| >700 | 33 | 5 | 7 | 1 | 3 | 1 | | 2 | | 1 | | 1 | |
| >800 | 14 | 2 | 4 | 1 | | | | | | | | | |

## Table II—(Continued)

June (10 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <300 | 3 | | | | | | | | | | | | |
| <400 | 11 | | | | | | | | | | | | |
| <500 | 19 | 2 | 1 | | | | | | | | | | |
| <600 | 20 | 9 | 3 | | | 1 | 1 | | | | | | |
| <700 | 23 | 13 | 5 | | 2 | 1 | | | | | | | |
| <800 | 11 | 10 | 7 | 6 | 2 | 2 | 2 | 1 | 1 | | 3 | | |
| <900 | 1 | | | | | | | | | | | 1 | 9 |
| <1000 | | | | | | | | | | | | | 1 |
| >200 | | | | | | | | | | | | | 3 |
| >300 | 1 | 1 | | | | | | | | 1 | 1 | 2 | 4 |
| >400 | 2 | 1 | 1 | 2 | 1 | | | | | 2 | 4 | 4 | 1 |
| >500 | 3 | 5 | 2 | 1 | 1 | 1 | 1 | 2 | | 3 | 6 | 2 | 1 |
| >600 | 5 | 8 | 2 | 5 | | 1 | 4 | 4 | | 1 | 5 | 1 | 1 |
| >700 | 20 | 6 | 6 | 4 | | 3 | 3 | 2 | | | 6 | | |
| >800 | 14 | 7 | 4 | 3 | | 1 | | 4 | 1 | 1 | 1 | | |
| >900 | 1 | | | | | | | | | | | | |

July (10 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <300 | 3 | | | | | | | | | | | | |
| <400 | 3 | 1 | | | | | | | | | | | |
| <500 | 8 | 1 | | | | | | | | | | | |
| <600 | 9 | 6 | | 1 | | | | | | | | | |
| <700 | 20 | 4 | 4 | 2 | 1 | | | | | | | | |
| <800 | 14 | 11 | 8 | 2 | 2 | 4 | 1 | 1 | 1 | 4 | 3 | | |
| <900 | | | | | | | | | | | | | 10 |
| >200 | | | | | | | | | | | | | 3 |
| >300 | | | | 2 | | | | | | | 2 | 2 | 1 |
| >400 | | | | 2 | | | | | | | 4 | 2 | 3 |
| >500 | 1 | 2 | | 2 | | 1 | | 1 | | | 4 | 5 | 2 |
| >600 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | | 8 | 2 | 1 |
| >700 | 6 | 8 | 2 | 3 | 1 | | 2 | 3 | 1 | 1 | 8 | 1 | |
| >800 | 22 | 6 | 5 | 2 | 2 | 3 | | 2 | | | 1 | | |

August (10 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <300 | 1 | | | | | | | | | | | | |
| <400 | 9 | | | | | | | | | | | | |
| <500 | 17 | 4 | 1 | | | | | | | | | | |
| <600 | 23 | 12 | 2 | | | | | | 1 | | | | |
| <700 | 22 | 10 | 6 | 2 | | 3 | 3 | | | 3 | 1 | | |
| <800 | | | | 1 | 2 | | | | | 1 | 4 | | 5 |
| <900 | | | | | | | | | | | | | 5 |

August (10 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| >200 | | | | | | | | | | | | | 1 |
| >300 | | | | | | 1 | | | | | | 1 | 6 |
| >400 | | | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 5 | 2 |
| >500 | 2 | 3 | 6 | | 1 | 3 | 2 | 4 | 2 | 1 | 2 | 2 | 1 |
| >600 | 11 | 6 | 4 | 6 | | 3 | 1 | 3 | 3 | 3 | 4 | 1 | |
| >700 | 20 | 8 | 6 | 4 | 1 | 2 | 3 | 4 | 1 | 1 | | | |
| >800 | 4 | 1 | | | | | | | | | | | |

## Table II—(Continued)

September (9 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <200 | 5 | 1 | 1 | | | | | | | | | | |
| <300 | 11 | | | 1 | | | | | | | | | |
| <400 | 13 | 3 | 1 | | 1 | | | | | | | | |
| <500 | 21 | 6 | 3 | 1 | 3 | | 1 | | | 1 | | | |
| <600 | 9 | 5 | 2 | 1 | | 3 | 1 | | | | 6 | 3 | |
| <700 | | | | | | | | | | | | | 9 |
| >100 | | | | | | | | | | | | | 5 |
| >200 | | 1 | 1 | | | | | 2 | 1 | | 5 | 3 | 2 |
| >300 | | 4 | 2 | 1 | | | 1 | 1 | 2 | | 3 | 3 | 1 |
| >400 | 4 | 3 | 2 | 1 | 2 | 4 | 1 | 3 | 2 | | 3 | 3 | 1 |
| >500 | 10 | 5 | 5 | 3 | 2 | 5 | 1 | 2 | | 1 | 5 | | |
| >600 | 16 | 3 | 4 | 2 | 1 | 2 | | | | | | | |

October (9 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <100 | 1 | | | | | | | | | | | | |
| <200 | 14 | 2 | 1 | | | | | | | | | | |
| <300 | 23 | 6 | 5 | | | | | | | | | | |
| <400 | 13 | 9 | 4 | 2 | 2 | 2 | 1 | | | 3 | 2 | | |
| <500 | 1 | | 1 | | | | | | | | | 3 | 6 |
| <600 | | | | | | | | | | | | | 3 |
| >0 | | | | | | | | | | | | | 1 |
| >100 | | | | | | | | | | 1 | 1 | | 7 |
| >200 | 3 | 2 | 3 | 1 | 1 | | | 3 | | 1 | 5 | 4 | 1 |
| >300 | 12 | 7 | 5 | 1 | 1 | | 1 | 2 | 2 | 1 | 7 | 1 | |
| >400 | 15 | 7 | 4 | 4 | 2 | | | 4 | | 1 | 1 | | |
| >500 | 1 | | 2 | | | | | | | | | | |

November (9 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <100 | 13 | 4 | | | | | | | | | | | |
| <200 | 22 | 12 | 6 | 1 | 2 | 1 | 2 | 1 | | | | | |
| <300 | 5 | 5 | 2 | 1 | 2 | 2 | 1 | 1 | | 3 | 6 | 1 | |
| <400 | | | | | | | | | | | | | 9 |
| >0 | | | | | | | | | | | | | 7 |
| >100 | 3 | 1 | 3 | 3 | | 1 | 2 | 1 | 2 | 1 | 2 | 3 | 2 |
| >200 | 17 | 5 | 7 | 4 | 1 | 2 | 1 | 2 | 1 | 1 | 3 | | |
| >300 | 7 | 4 | 2 | 2 | 3 | 2 | 1 | 1 | 1 | | | | |

December (9 years)

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11–20 | 21–30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <100 | 23 | 6 | | | | | | | | | | | |
| <200 | 17 | 9 | 8 | 6 | 3 | 1 | 1 | | 1 | | 1 | | |
| <300 | | | | | | | | | | | | | 9 |
| >0 | | | | | | | | | | | | | 9 |
| >100 | 11 | 1 | 4 | 1 | 1 | 5 | 3 | | | | | | |
| >200 | 20 | 12 | 4 | 3 | 2 | 1 | 3 | | | | | | |

# Frequency Distribution of Hourly Sums of Direct Solar Radiation at Potsdam

**By Hans Hinzpeter**

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The frequency distribution of direct solar radiation can be of importance in problems related to the building of apartment houses and in city planning. However, extended series of measurements of this radiation component are as yet available from only a few places. At the Potsdam Observatory (latitude 52° 23′ N, longitude 13° 04′ E, height 106m) direct solar radiation has been registered since 1930 with a Moll-Gorczynski pyrheliograph. The results have been published in the "Deutschen Meteorologischen Jahrbuch", Part IV, and should be typical for the flat countries of Central Europe.

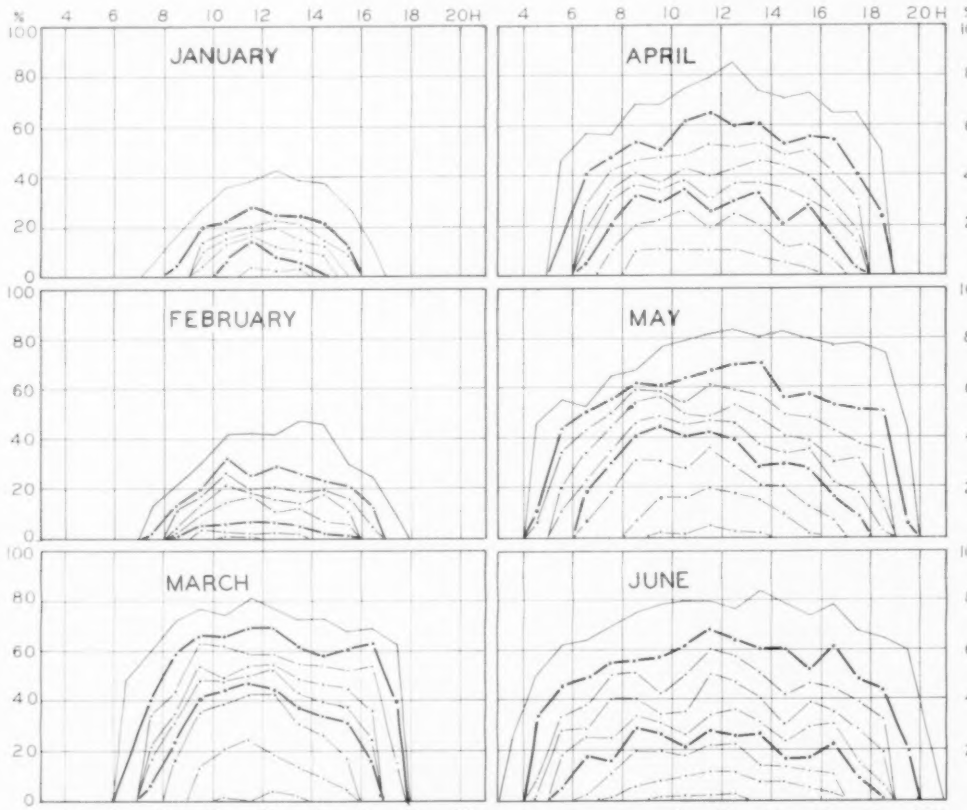


FIG. 1(a)—Frequency distribution of hourly sums of direct solar radiation, at normal incidence, at Potsdam ($\phi$52° 23′ N, $\lambda$13° 04′ E, h 106m); January–June.

The volumes for 1930 to 1953 present the following frequency distributions of hourly summations:

1. Direct solar radiation received by a surface area perpendicular to the solar beam for each month;
2. Direct solar radiation on a vertical wall facing north for the fifteenth of each month;

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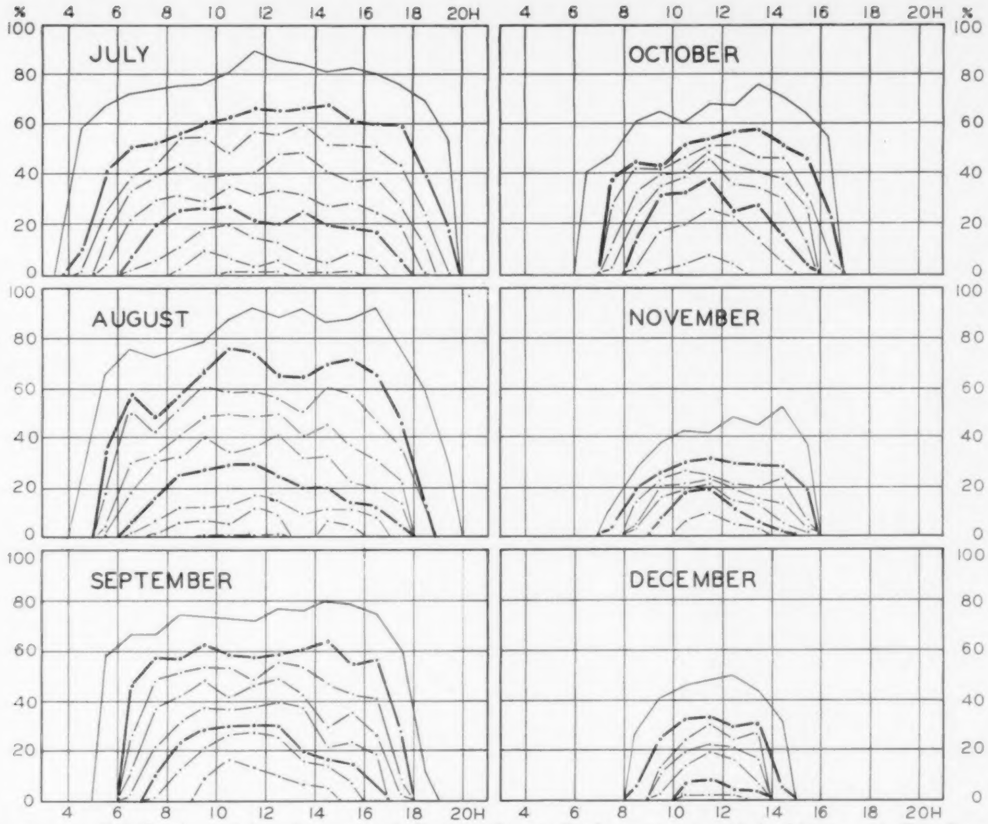


FIG. 1(b)—Frequency distribution of hourly sums of direct solar radiation, at normal incidence, at Potsdam ($\phi$52° 23′ N, $\lambda$13° 04′ E, h 106m); July–December.

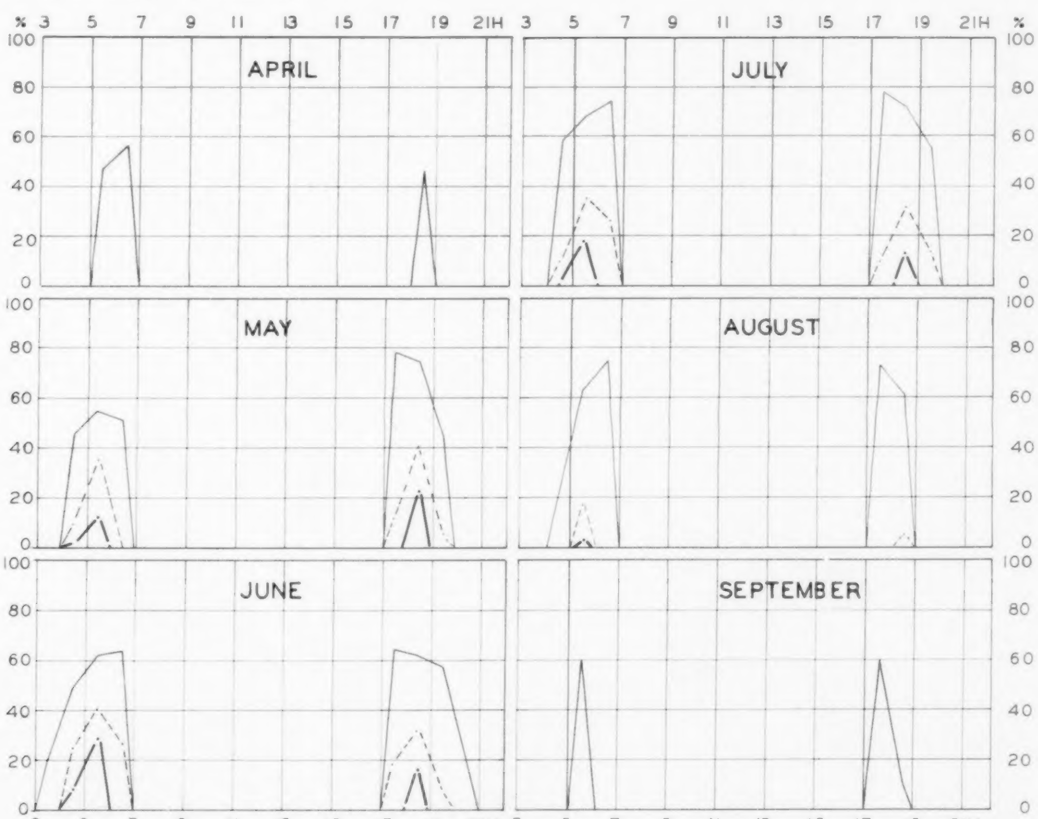


FIG. 2—Frequency distribution of hourly sums of direct solar radiation on a North-facing wall at Potsdam; April–September.

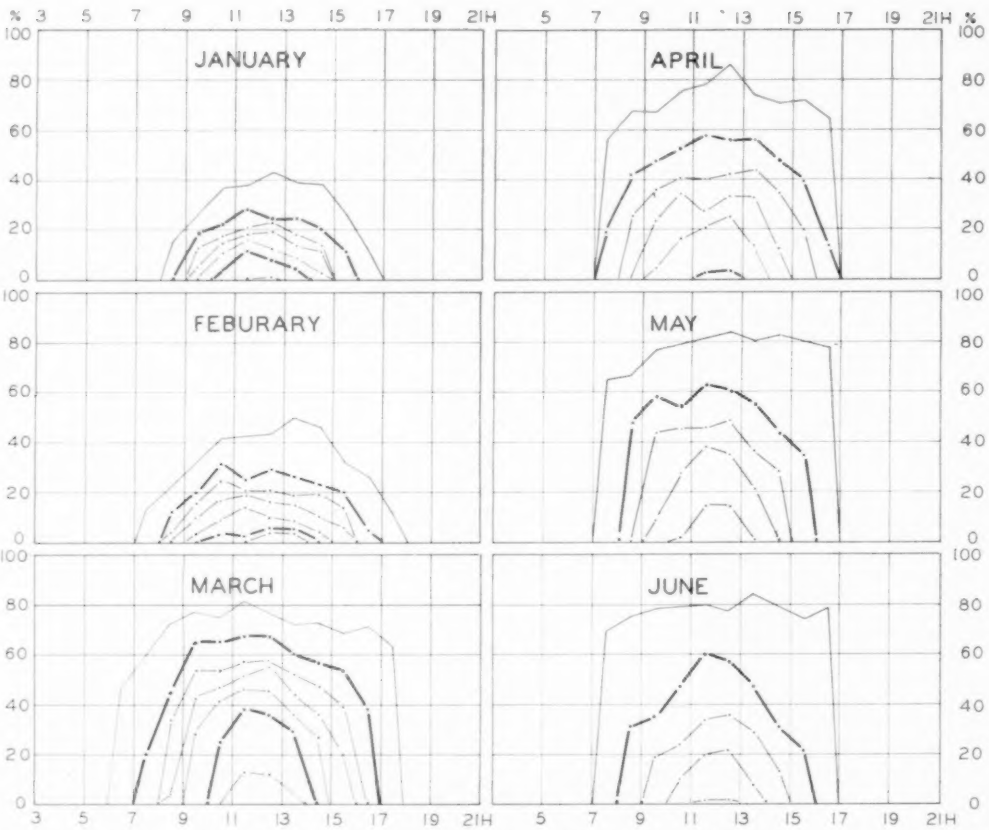


FIG. 3(a)—Frequency distribution of hourly sums of direct solar radiation on a south-facing wall at Potsdam; January–June.

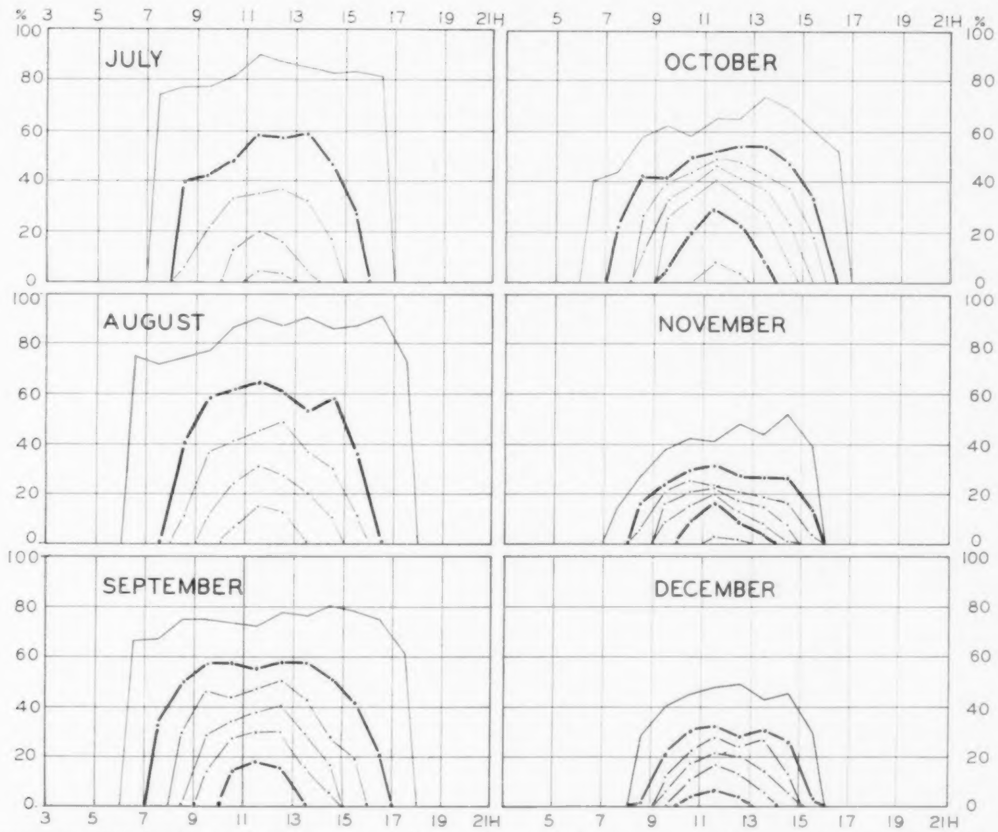


FIG. 3(b)—Frequency distribution of hourly sums of direct solar radiation on a south-facing wall at Potsdam; July–December.

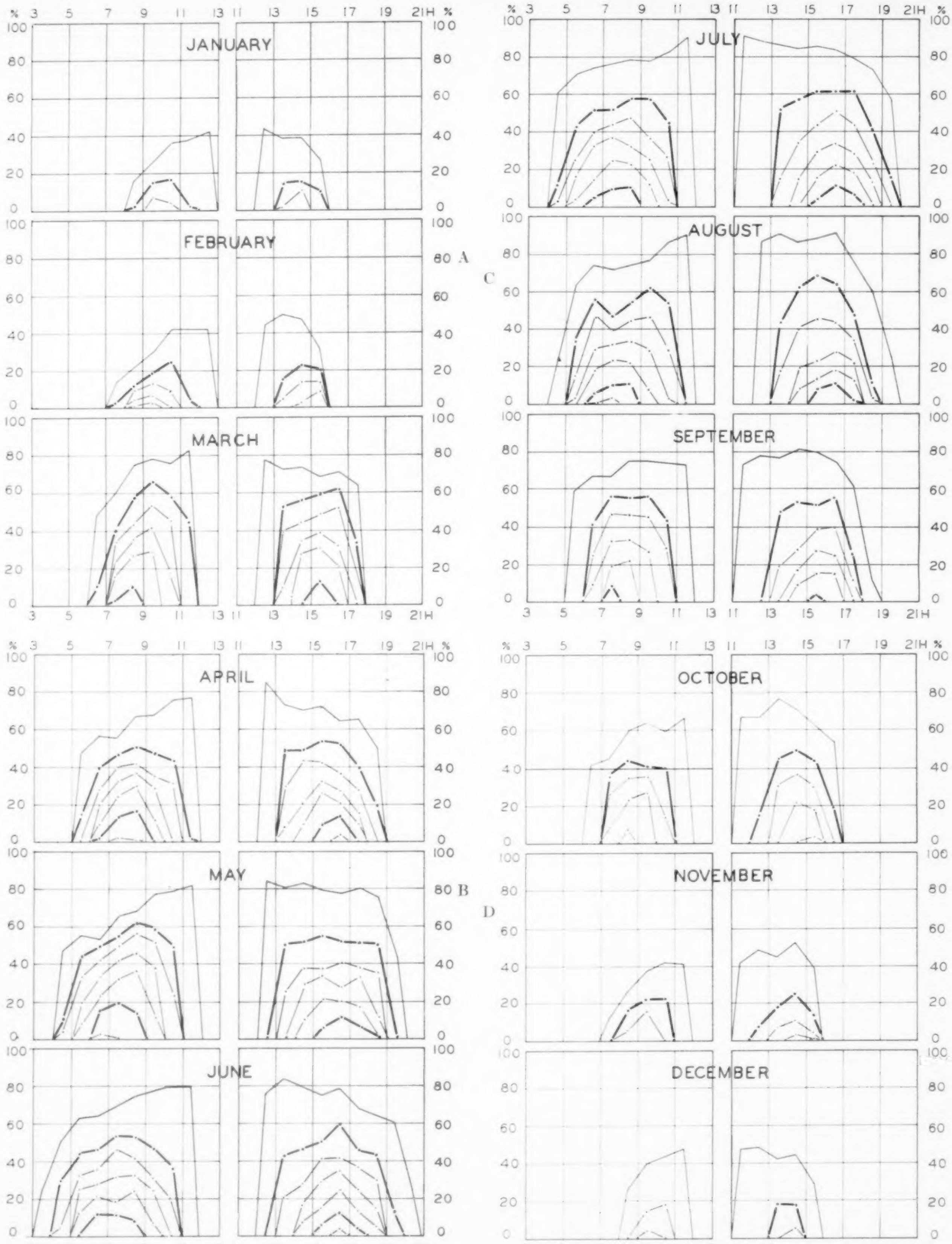
JANUARY
FEBRUARY
MARCH
A
APRIL
MAY
JUNE
B
JULY
AUGUST
SEPTEMBER
C
OCTOBER
NOVEMBER
DECEMBER
D

Fig. 4.

3. Direct solar radiation on a vertical wall facing east for the fifteenth of each month;

4. Direct solar radiation on a vertical wall facing south for the fifteenth of each month;

5. Direct solar radiation on a vertical wall facing west for the fifteenth of each month.

All frequency distributions refer to local mean time. Because of the time equation, incidence of radiation on the wall facing west commences before 12 noon during several months and terminates for the wall facing east sometimes after 12 noon.

In the graphical summaries presented in this contribution, Fig. 1 depicts the basic values of direct solar radiation at normal incidence; Fig. 2, the derived data for a north-facing wall; Fig. 3, the data for a south-facing wall; and Fig. 4, the data for east- and west-facing walls. Percentage distribution is shown on the ordinate scale and the time intervals (local mean time) on the abscissa.

In order to avoid unnecessary detail in the presentation, numerical values have been omitted. There should, however, be no difficulty in understanding the graphs. In all presentations the following categories have been used: 0, 0 to 10, 10 to 20 cal/cm$^2$, etc., the 0 category being the uppermost area. The intervals are connected by thin lines. To facilitate use of the diagrams, categories $<10$ cal/cm$^2$ and $<50$ cal/cm$^2$ have been separated from the categories $>$ 10 cal/cm$^2$ and $>50$ cal/cm$^2$ by thick lines. Only in the distributions for the wall facing north have the sums $<5$ cal/cm$^2$ also been separated from those $>5$ cal/cm$^2$ by a broken line. These connecting lines have no physical meaning; they serve purely for illustration, only the points for given time intervals being significant. In the evaluations for the vertical walls it was assumed that there was a random distribution of cloudy periods. The influence of turbidity was taken into consideration.

During the period of investigation (1930 to 1953) the 1913 revised Smithsonian scale was used to express intensities. A reevaluation to the new pyrheliometric scale, proposed in 1956, has not been attempted, since the reduction of all values by about 2 per cent is rather small and probably lies within the limits of error of all the frequency distributions.

FIG. 4(a)—Frequency distribution of hourly sums of direct solar radiation on east- and on west-facing walls at Potsdam; January–March.

FIG. 4(b)—Frequency distribution of hourly sums of direct solar radiation on east- and on west-facing walls at Potsdam; April–June.

FIG. 4(c)—Frequency distribution of hourly sums of direct solar radiation on east- and on west-facing walls at Potsdam; July–September.

FIG. 4(d)—Frequency distribution of hourly sums of direct solar radiation on east- and on west-facing walls at Potsdam; October–December.

# The Radiation Balance of Slopes

**By K. J. Kondratyev and M. P. Manolova**

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The radiation balance problem, at present, has rather a poor and one-sided solution. Only the inflow of direct solar radiation to differently oriented slopes has been closely studied. The precise theoretical formula has been derived for determining the flux of direct solar radiation to slopes of different exposure; numerous calculations, tables, and nomograms for defining the irradiation of slopes with direct solar radiation are being carried out by various workers.

The nature of the flux of scattered and reflected radiation to the slopes and the effective long-wave radiation of the slopes have scarcely been investigated; such studies have been reviewed (1, 2, 3). The computation of scattered and reflected radiation fluxes to the slopes as well as the effective radiation of the slopes is rather complicated owing to the fluxes being considerably non-isotropic.

As a rule, the radiation is assumed to be isotropic in all cases where practical calculations of the scattered and reflected radiation to the slopes are involved, simple formulae expressing the components of the slope radiation balance being derived with the help of the corresponding components of the radiation balance of a horizontal surface. However, it is not ascertained in what cases and with what accuracy the "isotropic" approximation can be valid.

The fluxes of scattered and reflected radiation to the slopes and the effective radiation of the slopes can be exactly determined either by measuring them for each specific slope, or by calculating the radiation influx to the slopes according to the given angular distribution of the radiation intensity. If the angular distribution of the scattered radiation to the slope is known, the flux of this scattered radiation can be estimated from the following exact formula:

$$D_S = \int_0^{2\pi} d\psi \int_{h(\psi)}^{\pi/2} J(h, \psi) \cos i \cos h \, dh \qquad [1]$$

where $J(h, \psi)$ is the intensity of the scattered radiation in the part of the sky with coordinates $h$ (angular height) and $\psi$ (azimuth); $h(\psi)$ is the lowest angular height of the point in the sky in the azimuth $\psi$ with respect to the horizontal plane; and $i$ is the angle which the radiation makes with the slope.

Similarly, the flux of the reflected radiation on the slope and effective radiation of the slope may be calculated. Both methods of determining the radiation balance components discussed here were used in this work.

Fluxes of scattered and reflected radiation to the slopes and the effective radiation of the slopes were calculated from theoretical formulae using numerical integration. The data necessary for the computations concerning the angular distribution of the energetic intensity of the scattered and reflected radiation were obtained by means of direct measurements carried out with Yanishevsky's pyranometer with an aperture angle of 10° and an evacuated thermo-element with a similar aperture. The instruments were mounted on theodolite devices. Radiation intensity was measured in 37 directions; for the vertical angles of 15, 40 and 65° in every 30° of azimuth, and in the zenith. This examination of the angular distribution of the energetic intensity of the scattered radiation was carried out for clear-sky and for overcast-sky conditions.

The angular distribution of the reflected radiation was measured at the level of different agricultural plants.

The angular distribution of the effective radiation intensity was obtained from the theoretical formula suggested by one of the authors (2):

$$f_h = f_0 \frac{0.25e^{-0.1w_\infty \operatorname{cosec} h} + 0.11e^{-0.5w_\infty \operatorname{cosec} h}}{0.25e^{-0.1w_\infty} + 0.11e^{-0.5w_\infty}} \qquad [2]$$

where $f_h$ and $f_0$ are intensities of the effective radiation in the direction of the angular height $h$ and in the direction of the zenith; and $w_\infty$ is the total quantity of water vapor in a vertical column of a single atmospheric section.

Radiation balance components of the slopes were directly estimated by means of a Yanishevsky pyranometer and by a ventilated Yanishevsky pyrgeometer. The instruments were mounted on theodolite devices so that their receiving planes could be oriented in any direction, including horizontal exposure to a free horizon. Thus, readings were taken for some isolated slopes located on a level surface, with the horizon unobstructed.

The numerical calculations of the radiation balance components of the slopes were made under the same schematic conditions.

This program of observations was carried out in different geographical locations: near Leningrad, in the Crimea and in the Khochetav region (the Kazakh SSR).

The relative values of the radiation balance components of the slopes were derived from the measurement and calculation data, i.e., the ratio between the radiation balance components of the slope and the corresponding components of the radiation balance of a horizontal surface.

The radiation balance of a horizontal surface has now been studied rather well. So, it may be assumed that values of the components of the radiation balance of a horizontal surface are available. Hence, the radiation balance of the slope will be completely determined in the case where the relative values of its components and those of the horizontal surface are known, at a given place. The relative values of the radiation balance components of the slopes have greater similarity as compared to the absolute ones; besides they can be measured more exactly.

Calculation of the scattered radiation fluxes to the slopes for a cloudless sky has been carried out for slopes with angles of inclination of 15, 30, 60, and 90°, oriented by azimuths of 0, 90, 180, and 270°, respectively, to the solar azimuth. The fluxes of the reflected radiation on the slopes were calculated with the assumption that the reflected radiation is isotropic. Slopes of inclination up to 30° have only a small (up to 10 per cent) portion of the reflected radiation in the scattered radiation flux, and, in this case, the "isotropic" approximation will involve a negligible error. The flux of the reflected radiation on the steep slopes may constitute an appreciable part of the general flux of the incident radiation (scattered and reflected); that is why it is necessary to take the angular distribution of the reflected radiation intensity into account when making accurate calculations. So, this was done in several cases to estimate the influence of the non-isotropic angular distribution of the reflected radiation intensity.

Fig. 1 presents the results of the calculation for the dependence of the ratio $(D_S + r_s)/D_H$ on the angle of inclination and on the slope azimuth for a solar elevation of 48° with cloudless sky. Here $D_S$ and $D_H$ are the scattered radiation fluxes to the slope surface and horizontal surface; $r_S$ is the reflected radiation flux to the slope surface; $\alpha$ and $\psi$ are the inclination and azimuth angles of the slope (the latter being the deviation from the solar azimuth). As shown in the figure, the dependence of the relative flux of the scattered radiation upon the inclination angle of the slope is different for slopes of different azimuth.

The curve corresponding to the isotropic approximation $((1 + \cos \alpha)/2)$ demonstrates that the dependence of the relative flux of the scattered radiation upon the inclination of the slope is essentially different from that which is observed under real conditions. This means that, in this instance, the isotropic approximation is not satisfactory.

The direct measurements of the scattered and reflected radiation fluxes to the surfaces of the slopes show the same dependence of the value of the scattered radiation relative flux upon the inclination and azimuth angles of the slope.

The measurements and calculations of the scattered radiation fluxes to the slopes were also carried out for conditions of overcast sky. The inflow of the scattered radiation to a slope, in this case, depends upon the inclination angle of the slope but not upon its azimuth. Therefore, the isotropic approximation proves to be satisfactory for the conditions of overcast sky (dense cloudiness). However, when the cloudiness is not uniform or is partially transparent, the ratio $(D_S + r_s)/D_H$ is a function not only of the inclination of the slope but also of its azimuth; and, hence, the isotropic approximation for this condition proves to be unrealistic. Thus, in the majority of cases the isotropic approximation gives unsatisfactory results when calculating the scattered radiation fluxes to slopes.

, As mentioned above, the reflected radiation fluxes to the slopes were calculated from the exact formula, the angular distribution of the reflected radiation intensity being taken into account, and by the formula of isotropic approximation. In practice, the difference between exact and approximate values becomes appreciable only in case of steep slopes ($\alpha > 50°$) where, when the sun is low, it can amount to 30 per cent. The calculations were made for a smooth surface (barley field) and cloudless sky. Thus, in the case of a smooth surface, the angular distribution of the reflected radiation intensity should be taken into account in exact calculations of the reflected radiation reaching the slope.

The measurements and calculations of the fluxes of the total sun and sky radiation to various slopes, when the sky is clear, proved that the non-isotropy of the scattered radiation should be taken into account where the sun is low ($h_{\odot} < 15°$), when the scattered radiation constitutes a considerable portion of the total radiation.

This can be seen in Fig. 2 which presents curves showing the dependence of the total radiation relative flux to slopes upon the inclination and azimuth of the slope. These curves are drawn according to the meas-

urement data (heavy lines) and to the calculations where the assumption is that the scattered and reflected radiation is isotropic (fine lines). The dashed curves are characteristic of relative values of the direct solar radiation fluxes $S_s/S_H$. Fig. 2 corresponds to a solar elevation $h_{\odot} = 15°$. For a high sun, when the scattered radiation is a negligible portion of the total sun and sky radiation, the total radiation fluxes to the slopes can be calculated by isotropic approximation. The observations carried out with different solar elevation have shown that with the increase of the sun height above the horizon, the dependence of the total radiation relative fluxes to the slopes upon the slope azimuth decreases. Measurements of the total radiation during conditions of partial and overcast transparent cloudiness have shown that the character of the distribution of the total radiation fluxes to various slopes remains the same as for cloudless sky conditions.

Curves based upon the measurement data for cloudless sky, were prepared of the dependence of the total radiation relative fluxes upon solar elevation, slope inclination, and azimuth. These curves for broad ranges of slope inclination and solar elevation and for four (relative to the sun) orientations of slope are given in Figs. 3, 4, and 5 (the slope azimuth to the sun is 0, 90 or 270, 180° respectively).

The total radiation fluxes for intermediate values of parameters can be attained by means of linear interpolation. The curves presented allow approximate estimation of the relative values of the total radiation to the slopes when the sky is cloudless and the albedo of the underlying surface is about 20 per cent. Comparison between the measured values of the relative fluxes of the total radiation to the slopes and those determined by the curves in Figs. 3, 4, and 5 showed that the average difference between the two sets is 10 per cent.

The fluxes of total radiation in the case of an overcast sky can be calculated by isotropic approximation. In case of partial cloudiness, linear interpolation can be applied in order to determine the total radiation fluxes to a slope:

$$g_n = g_0(1 + cn). \qquad [3]$$

Here $g_n$, $g_0$ are relative values of the total radiation fluxes to a slope, respectively, with cloudiness of fraction $n$ and with a cloudless sky. The empirical coefficient $c$ is determined as follows:

$$c = \frac{g_1 - g_0}{g_0}$$

where $g_1$ is a relative value of the total radiation flux with overcast sky.

The diurnal variation of the total sun and sky and

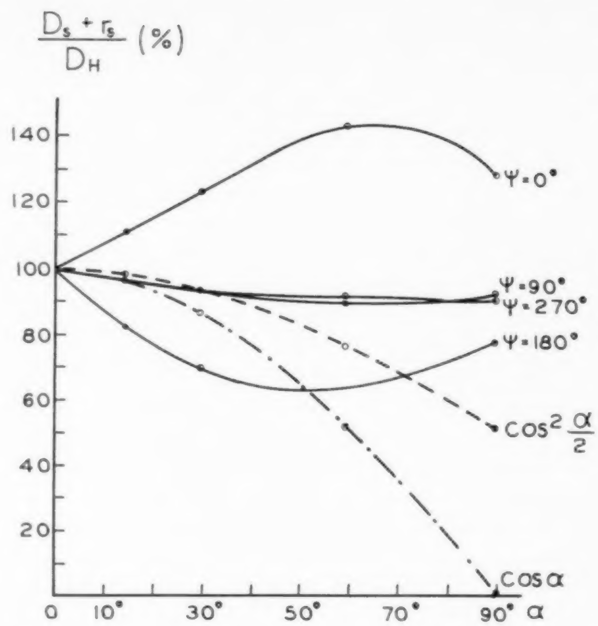


FIG. 1—Dependence of the ratio $(D_S + r_S)/D_H$ on the inclination $(\alpha)$ and the azimuth $(\psi)$ angles of the slope for solar elevation $h_{\odot} = 48°$ (5 July 1953: cloudless sky $D_H$ = 0.18 cal/cm²/min).

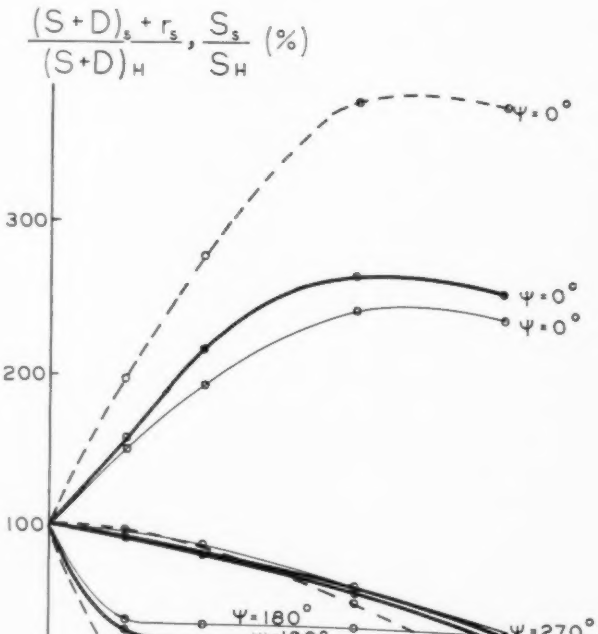


FIG. 2—Dependence of the ratio $[(S + D)_S + r_S]/[(S + D)H]$ (%) according to the measurement data (heavy curves) and calculation data with the aid of isotropic approximation (fine curves), and $S_S/S_H$ (dashed curves), on the inclination $(\alpha)$ and azimuth $(\psi)$ angles for solar elevation $h_{\odot} = 15°$ (12 July 1953: cloudless sky).

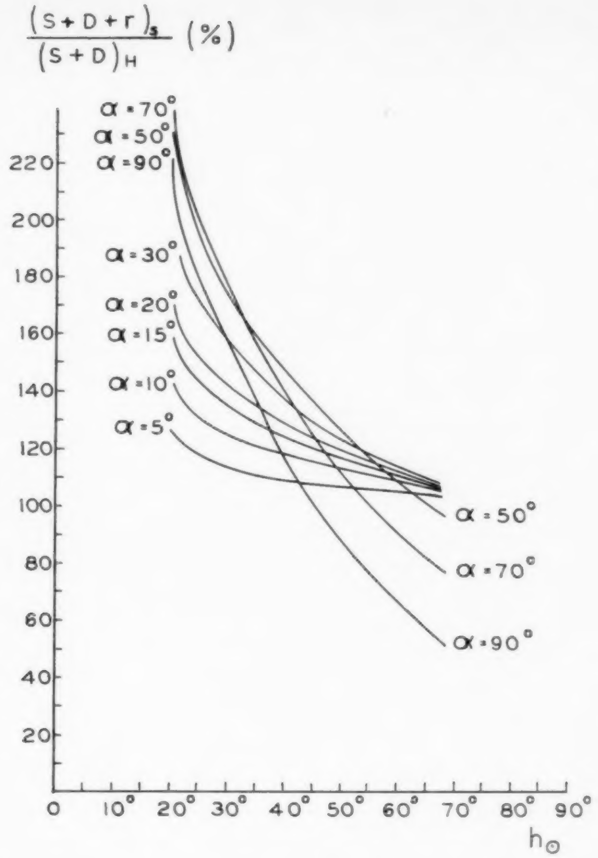


FIG. 3—Dependence of the relative total radiation flux on the solar elevation, for slopes with different inclination and azimuth $\psi = 0°$ (cloudless sky).

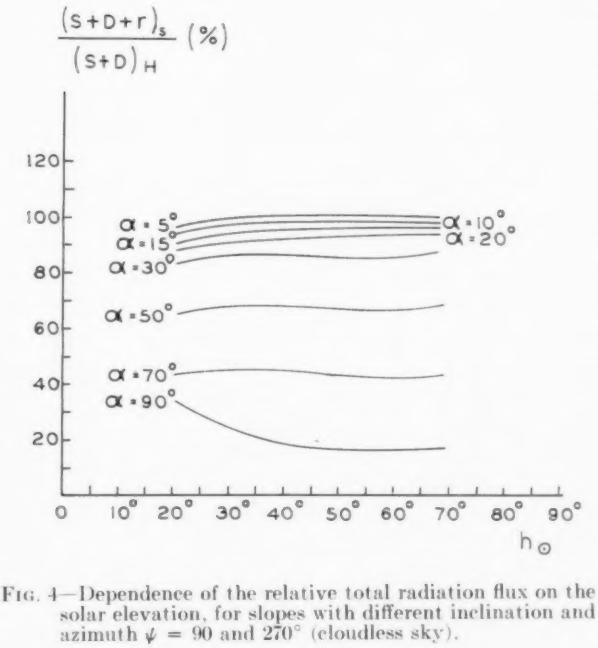


FIG. 4—Dependence of the relative total radiation flux on the solar elevation, for slopes with different inclination and azimuth $\psi = 90$ and 270° (cloudless sky).

the reflected radiation fluxes when the sky is cloudless has been investigated by measurement data for slopes having inclinations of 5, 10, 15, 20, 30, 50, 70, and 90°, oriented to the south, north, east, and west, for a location in latitude $\varphi = 45°$. The observations showed that the variations of the scattered and reflected radiation to slopes (both gentle and steep) of different orientation nearly coincide with that of scattered and reflected radiation to a horizontal surface. The variation of the scattered and reflected radiation fluxes is practically equal for the southern and northern slopes of various inclination. Only western and eastern steep slopes have a marked difference.

The near independence of the diurnal variation of the scattered and reflected radiation on the slope inclination is apparently caused mainly through the tendency for compensation of the decrease of the scattered radiation inflow (with increase in slope inclination) by the increase in the reflected radiation inflow.

The variation of the total radiation for slopes of various orientation with inclinations up to 10° is almost independent of the slope orientation but differs slightly from the variation for a horizontal plane. The variation of the total radiation for slopes with greater inclination depends essentially on the slope orientation and inclination.

The variation of the character of the total radiation throughout the day (depending on slope orientation and inclination) is caused first of all by the variation in the direct solar radiation inflow.

By means of a planimetric study of the curves of the diurnal radiation fluxes, the relative daily sums of the total and scattered radiation for various slopes have been calculated (these data apply to the conditions in the Crimea, i.e., in latitude about 45° north).

The calculations showed that the north, east, and west oriented slopes receive less total radiation per day than a horizontal surface, the daily sums decreasing with increase in the slope inclination. The inflow of the total radiation to slopes of southerly orientation, with inclination up to 30°, is somewhat greater than to a horizontal surface, but the more steep south slopes receive less total radiation than a horizontal surface. Thus, south slopes in latitude 45° have little advantage over a horizontal surface.

The daily sums of the scattered and reflected radiation for various slopes differ but slightly from the corresponding daily sum for a horizontal surface. The difference is only appreciable, in general, for slopes of inclination greater than 50°, the daily sums of the scattered and reflected radiation for steep slopes being greater than for a horizontal surface. The above-mentioned fact renders it possible to estimate, approximately, the scattered and reflected radiation in the

daily sum of the total radiation for a slope, by means of simple addition of the scattered radiation sum of the horizontal surface to the direct solar radiation sum for the slope.

The daily sums of the total sun and sky radiation to the slopes were also calculated, by "isotropic" approximation for the scattered and reflected radiation, from the formula:

$$\sum(S + D + r)_s = \sum S_s + \cos^2 \frac{\alpha}{2} \sum D_H + \sin^2 \frac{\alpha}{2} \sum r_H . \quad [4]$$

Here $S$, $D$, $r$ are the fluxes of direct, scattered and reflected radiation, and $\alpha$ is the slope inclination.

Comparison between the daily sums of the total radiation calculated by formula (4) and those measured has shown that use of formula (4) yields sufficient accuracy for practical purposes. The daily sums of the total radiation to slopes can be calculated by formula (4), in case of overcast sky, as well as cloudless sky.

The long-wave effective radiation of the slopes was calculated by a formula of type (1) in the case of a cloudless sky and was measured with the help of a ventilated pyrgeometer. The measurements were carried out on clear nights for surfaces having the inclination angles of 5, 10, 15, 20, 30, 50, 70, and 90°, oriented in the four cardinal points.

The calculations and measurements showed that the ratio of the effective slope radiation ($J_S$) to the effective radiation of a horizontal surface ($J_H$) depends on the inclination of the slope but is independent of its azimuth. The results of the measurements and calculations are given in Fig. 6 (the curves correspond to the calculation data). From the above data it is clear that the value of the relative effective radiation of the slope depends only slightly on the total water vapor content in the atmosphere $w_\infty$. Hence, the effective radiation of the slopes, when the sky is cloudless, can be calculated from the effective radiation of a horizontal surface and from the values $J_s/J_H$ corresponding to the average curve in Fig. 6. For the slopes of inclination up to 30°, the effective radiation can also be calculated from the cosine law.

For the investigation of the variation in the radiation balance change, the radiation balance of a blackened surface with various orientations was measured. The character of the ratio of the radiation balance of the slope to the radiation balance of a horizontal surface (depending on the slope inclination and azimuth) is, in general, the same as for the value of the relative flux of the total radiation.

Slopes directed towards the sun have a negative radiation balance with some values of the inclination angle. As the slope inclination increases, the radiation balance passes through zero at values of the inclination where the direct solar radiation does not reach the slope ($\alpha \geqq h_\odot$). The steep slopes ($\alpha > 50°$) have a positive balance again, perhaps because of the increase in the reflected radiation inflow to the slope and the decrease in the effective radiation. As the sun rises higher above the horizon, the negative zone of the radiation balance becomes smaller.

Overcast cirrus clouds appreciably diminish the influence of the azimuth orientation on the value of the relative radiation balance of a surface.

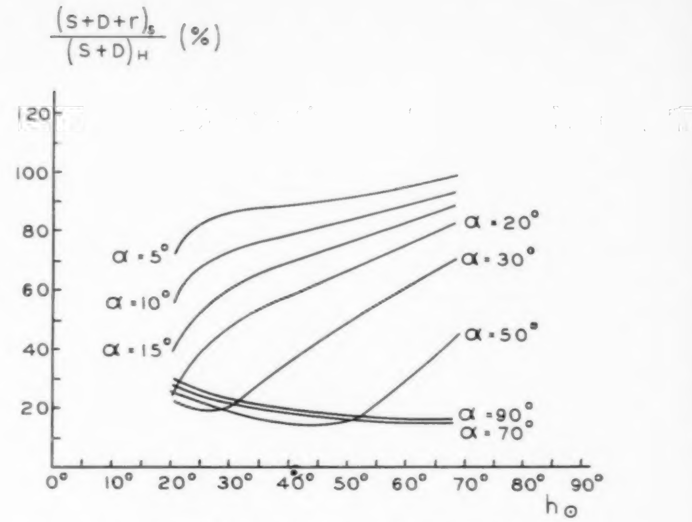


FIG. 5—Dependence of the relative total radiation flux on the solar elevation, for slopes with different inclination and azimuth $\psi$ = 180° (cloudless sky).

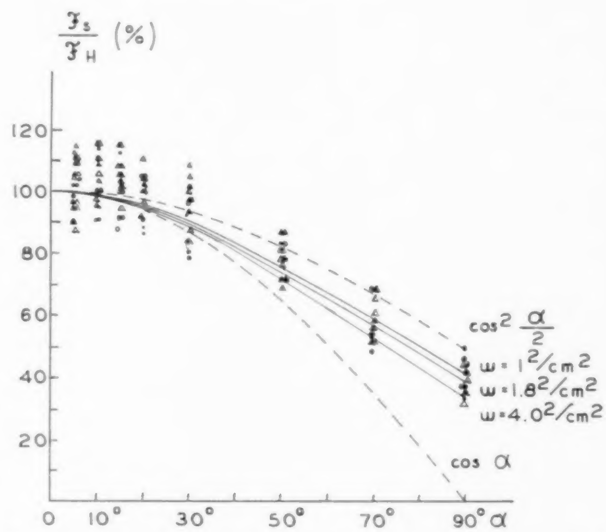


FIG. 6—Dependence of the relative effective (long-wave) radiation on the slope inclination (cloudless sky: ○ N., ● S., △ E., and ▲ W.).

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# The Number of Days with Solar Radiation Above or Below Specific Values

**By S. Fritz and T. H. MacDonald**

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There have been a great many measurements of solar radiation taken in various ways all over the world. Processing of these data in special ways for practical applications of solar energy, can make the data more useful. This paper analyses solar radiation data of this kind in a way which make them useful in design of solar house heating systems, in applications of solar energy to house cooling, and for other application where energy storage is necessary. In the case of solar house heating, in some climates it is necessary to provide heat storage for several days unless auxiliary heating systems are furnished. The heat storage will be required to take care of days when the amount of solar energy received at the house, due for example to cloudiness, is less than the heat load required to heat the house on a particular day. Thus, to design the heating system properly, it would be necessary to know the consecutive number of days for which one is likely to need storage or auxiliary heating.

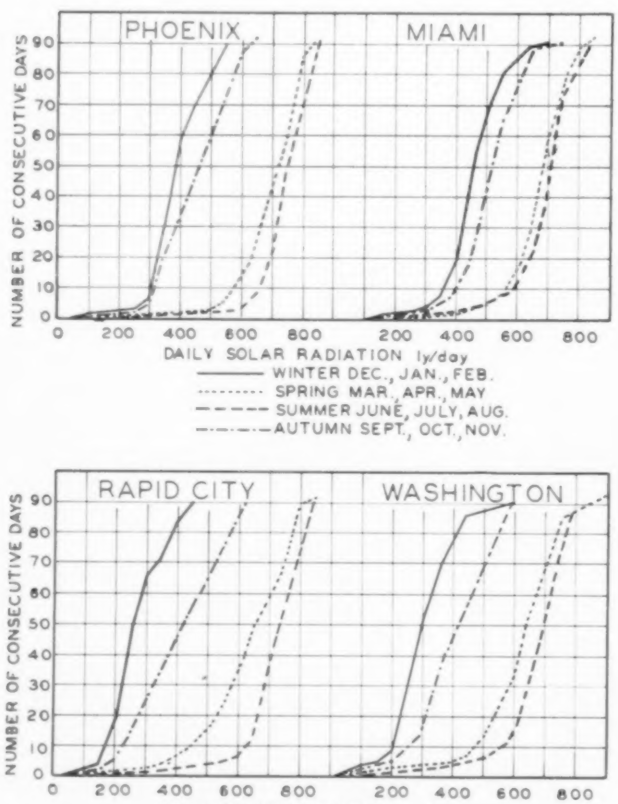


FIG. 1—Mean maximum number of consecutive days with radiation below specific values at Phoenix, Miami, Rapid City, and Washington.

In the case of house cooling in the summer, it is of interest to know the number of days with solar radiation above certain values, to indicate the number of days on which large amounts of heat might have to be removed from the house; the number of consecutive days with solar radiation above certain values is also needed in the house heating problem, to indicate the maximum number of days on which excess solar radiation is available for storage.

In cases where chemical storage batteries are used, for example to run a communications link, the batteries may be charged by using solar energy. The storage capacity of the batteries may be so large that it is not important to know the number of consecutive days with energy above or below certain values.

Other uses of this type of data, as in water evaporation systems, can be cited. Examples of all three types of arrays of data are shown in Figs. 1, 2, and 3. Fig. 1 gives the mean maximum number of consecutive days with solar radiation below given values, for four cities, namely, Phoenix (Arizona), Miami (Florida), Rapid City (South Dakota), and Washington, D. C. For each city, four curves are given, one for each of the seasons of the year. In compiling these curves the maximum number of consecutive days was determined for each year; the average of these maxima is plotted

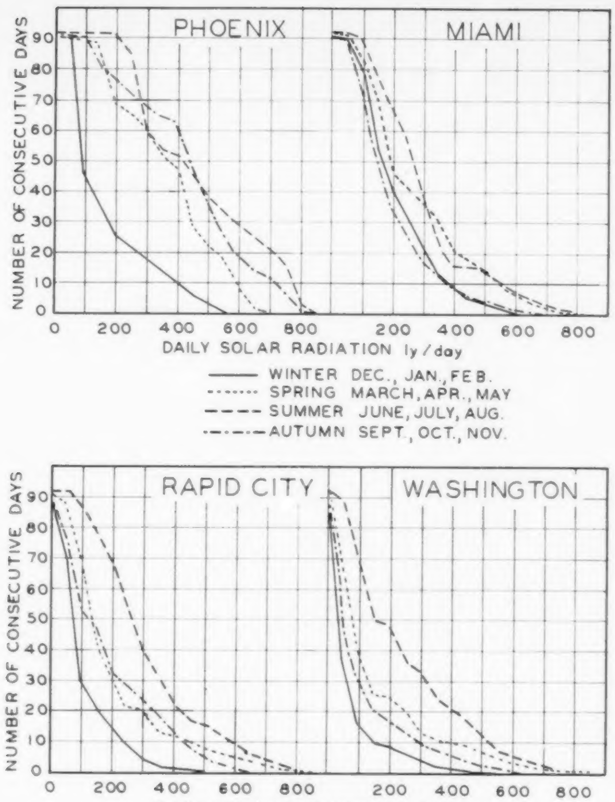


FIG. 2—Mean maximum number of consecutive days with radiation exceeding specific values at Phoenix, Miami, Rapid City, and Washington.

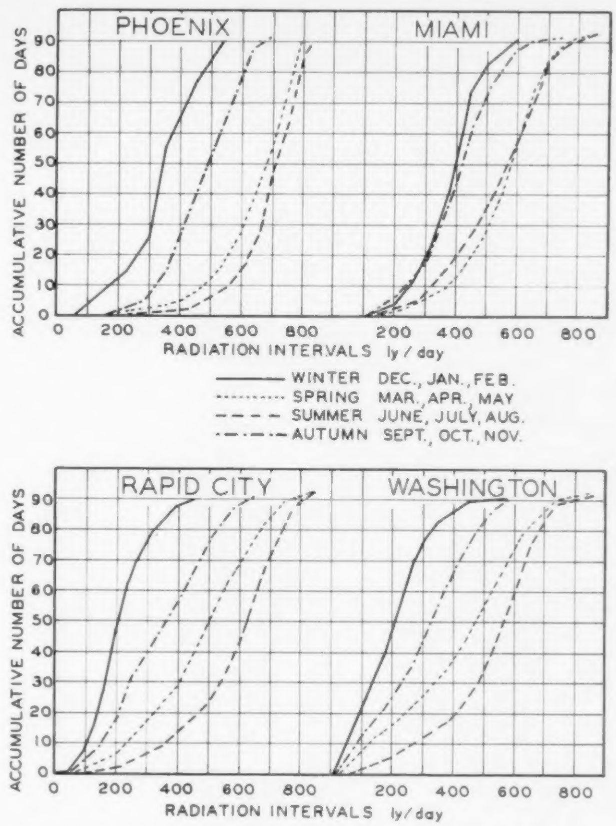


FIG. 3—Accumulative number of days with radiation below indicated values at Phoenix, Miami, Rapid City, and Washington.

in Figs. 1 and 2. In applying these data (which are based on the average for the six years 1952 through 1957) to the design of the heating system for house heating, one should consider the winter months. The curves indicate that, at Miami and Phoenix, one should expect that in an average season there will be only five consecutive days at most when the solar radiation on a horizontal surface will fall below 300 ly/day (ly = 1 langley = 1 cal/cm$^2$). In Rapid City and Washington, however, more than 50 consecutive such days will occur. If one were to design a heating system in which 300 ly/day were required to heat the house comfortably, then one may see that at Rapid City and Washington this system would not be practical without substantial auxiliary heat. At Miami and Phoenix, relatively small storage or auxiliary heating would be required. At Rapid City and Washington, heating systems requiring only about 150 ly day would be practical.

Fig. 2 shows the average maximum number of consecutive days with solar radiation exceeding given values for the same cities. For example in Phoenix, in an average summer season, there would be a maximum of about 38 consecutive days with solar radiation more than 500 ly/day. This would represent one of the parameters to be considered in designing a house cooling system; the data would be useful for estimating the cooling load required and for estimating the amount of energy available for use in the cooling system.

Finally, Fig. 3 indicates the number of days, consecutive or not, on which the radiation is below certain values. One might consider, for example, a system in which 300 ly/day are needed; assume that a chemical storage battery is used in the system. There would be, in an average winter season, 26 days at Phoenix on which some storage would be required since the number of days with radiation below 300 ly/day is 26. Alternatively, there would be 64 days during the winter season on which the radiation would be above 300 ly/day so that some storage would be possible on those days. In such a system, however, storage would be required on 77 days at both Washington and Rapid City in winter.

It should be pointed out that these data are based on measurements of solar radiation made on a horizontal surface throughout the day. For some applications, for

example in house heating in winter, it would be better to have the solar radiation data for sloping surfaces or for vertical surfaces facing south, since most efficient solar heating design would include collectors facing in those directions. However, there have been studies of the relation between radiation received on horizontal surfaces and radiation received on vertical and sloping surfaces. And it should be possible to get a rough estimate which would relate the data of Figs. 1, 2, and 3 to the data required for the particular surfaces. On the other hand, in some cases, the radiation received on a horizontal surface is actually the one required. This is, for example, true for the solar house cooling systems required in summer, when during much of the day at low latitudes the sun is high in the sky; and for design purposes it may be easier to construct a solar radiation system in which the collector is horizontal. For any particular application, a very special measurement would probably be required for highly accurate data. But the most frequently available measurement is the solar radiation on a horizontal surface; and to make use of the available data, it is necessary to make auxiliary studies relating the radiation on horizontal surfaces to the radiation on the properly-oriented surface.

## ACKNOWLEDGMENT

We thank Mr. B. J. LeBlanc for assembling and arraying the data in a suitable form for analysis.

# Practical Aspects of Solar Swimming Pool Heating

**By Douglass E. Root, Jr.**

Engineering Consultant, Orlando, Florida

**Since 15,000 home swimming pools are being built in the United States each year, pool heating has become important to the solar engineer. A sun trap, using a pool as its own heat collector, is discussed along with more conventional types of solar pool heaters. Solar and fossil fired heaters are compared and the advantages of all are considered. The possibilities of a floating liquid film to effect a sun trap is suggested as a most promising area of experimentation.**

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Since the major losses from swimming pools are due to radiation and a combination of convection and evaporation, a heating system which reduces these losses does not have to add as much heat to maintain any given pool at a comfortable level as does one which does not reduce these same losses. As concerns solar heat collectors a system can be devised which also eliminates the necessity of using expensive separate solar heat collectors.

The thought of utilizing an entire swimming pool as its own heat collector is not a new one. Dr. George Löf has utilized a mylar cover stretched on a pipe frame for several years to successfully maintain a comfortable temperature in the pool at his home in Denver. It is pictured in *The Sun at Work*.[1]

The problem has been two-fold: the tediousness of moving the cover on and off of the pool each time it is used, and the problem of permanently cementing mylar strips together when they must be in contact on one side with water or fully saturated air; for a pool, when covered, becomes a full reflux solar still.

With the advent of du Pont teslar film, which can be heat sealed to itself and to various other materials, the light transparent, heat opaque pool cover becomes a great deal less cumbersome to construct and to emplace and remove.

One of the simplest methods is to construct a large life raft type plastic unit in which the protective plastic sheet floats on pontoons on the pool surface. When deflated, this unit can be rolled up for storage. Placed on the pool surface with the interconnected pontoons partially inflated (with the positive outlet of a vacuum cleaner), the unit can be floated on the water, plastic sheet up. If the pontoons are properly arranged when they are fully inflated while the cover is in place they will hug the pool walls, almost eliminating the evaporative loss. Even in pools of uneven shape where a tight seal to the walls is impossible to obtain, such a cover substantially reduces the evaporative, convective, and radiant losses and acts as a very effective heat trap for the sun's rays.

If the paint on the pool walls and bottom is normally light in color a black plastic sheet may be placed in the bottom of the pool to improve the spectral distribution of reradiated wave lengths. It is desirable that all reradiation be in the heat wave length range since it is to these wave lengths that plastic films are most impervious.

The big disadvantage of the pool cover is that it must be removed for swimming—but conversely it keeps dirt and leaves out of a pool which is used only periodically.

It might be well to consider the use of more conventional solar heat collectors for pool heating by comparison.

The use of separate heat collectors placed in series with the filter system has one very distinct disadvantage. This system does not reduce heat losses from the pool.[2] Oil, gas, or electric heaters with a capacity in the neighborhood of 200,000 Btu/hour can reheat a pool after a cool period within a few hours of the next day. Pools heated by collector panels may be several days recovering heat losses unless the owner has installed a large heat collecting panel. Unfortunately a good many under sized solar pool heaters have been installed throughout the country, because the designers overlooked the magnitude of the daily heat losses.

Adequately sized conventional piped collectors are too expensive to construct for general pool heating use. The alternative, fortunately, is simple. The pool water need not be circulated under great pressure, so

it can flow by gravity down a black waterproof insulated sheet or between two thin plates under a light-transparent, heat-opaque cover and either trickle through a pipe back into the pool or be pumped back by a small auxiliary pump if this is more convenient. This system eliminates expensive tube type construction. Since these collectors are cheaper to make than tubed ones it is possible to install an adequate separate heat collector area without burdening the purchaser with too large an initial investment.

At the present time cetyl acid is being used to prevent small ponds in fish breeding areas from drying up when the rainfall is low. It is said to reduce evaporation by 50% and to spread itself so thin that only a few drops would adequately coat the surface of an average size swimming pool. Of course it will not appreciably reduce convective losses, and its film appears to lack the optical characteristics to produce a heat trap. But there may be some substance which when dropped in minute quantities on the surface of the pool will be non toxic, reduce evaporation, and form a film which is light-transparent, and heat-opaque. Such a compound might also make possible the use of ponds as heat sources for home heating.

To summarize, the pool cover produces a large collecting area at a very low cost per square foot. It reduces the heat losses from pools when they are not in use. It protects them from dirt, leaves, and the like. But at best it is somewhat cumbersome to remove and replace.

Separate solar collecting panels, since they do not reduce pool heat losses, must be large and thus are more expensive. Their use does permit continuous use of the pool. Because of their high cost conventional piped collectors are less advantageous generally than low pressure gravity flow deck collectors (which in one form are actually full reflux solar stills).

The chemical film offers possibly the most rewarding challenge in the solar pool heating field today, and its development could well broaden the entire field of solar application.

Despite some of the physical disadvantages of solar pool heaters the high cost of operating oil, gas, or electric units places solar energy in an extremely strong economic position with regard to swimming pool heating.

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# Conversion of Sun Radiation to Electricity

By Grandison Gardner

**The author has previously argued that our outer atmosphere consists primarily of charged nuclear particles, and he suggests an apparatus, without moving parts, which, if placed in a region containing a large number of such particles, would separate and capture them by a method analogous to the separation of ions in a storage battery.**

**He visualizes a small light weight device for conversion of minute quantities of electric current, such as might be useful in satellite projects. He suggests also that such apparatus might be practically used, or at least tested, on the earth in high altitude localities. In such localities, large absorbing surfaces and heavy magnets would be usable, and they might supply very useful quantities of electric power.**

**The article includes a simplified sketch to facilitate explanation.**

The following is a description, for whatever it may be worth, of a suggested, but untried, method of converting sun radiation directly to electricity. This method, with small and light weight apparatus, would undoubtedly serve to produce minute quantities of electricity. In high altitude locations, on the earth's surface, where large collection plates and heavy magnets would not be prohibitive, it might be possible to convert very useful quantities without the use of any conventional mechanical apparatus.

The fact that much of our atmosphere at extremely high altitudes is ionized, has been quite well established for a long time, and the author of this suggestion has contended for some time that this ionization is due to charged material particles (helium and hydrogen atoms and smaller particles) radiated directly from the sun. We are all familiar with the continuous and violent explosion of the surface content of the sun, and we know that these exploding materials must be highly

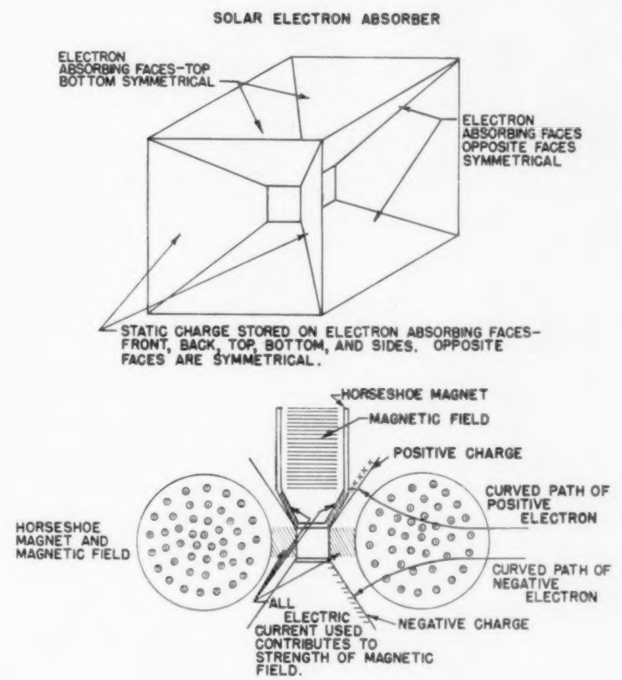


FIG. 1

dissociated and highly charged electrically and that great quantities of these have velocities sufficient to escape from the sun. A fraction of these charged escaping particles are thrust into our atmosphere to produce its characteristic ionization. Another great quantity reaches us with such speeds as to start an everlasting revolution about us, when they reach the earth's gravitational field. Each becomes a little moon. The author has previously suggested that, beyond our fluid atmosphere is another very substantial atmosphere consisting primarily of these orbiting particles, nearly all of which are electrically charged.

The phenomenon of electrolysis and the voltaic cell are familiar to nearly everyone with a high school

education, and these indicate how ions can be separated in liquids to produce electrical apparatus and devices of unlimited practical usefulness. It has been known prior to the present century that the path of charged particles can be changed by either an electrostatic or a magnetic field and that positively and negatively charged particles are deflected in opposite directions.

The accompanying diagrams are intended to show six inverted angular funnels, compromising between maximum surface area and minimum weight, which, if placed in the upper or the outer atmosphere, would be continuously showered by charged particles from all directions. The funnel surfaces are in pairs and made of materials analogous to the plates of a storage battery such that they would stop and hold a maximum number of particles. The plates are in pairs with one facing in each direction receiving negative particles and one receiving positive particles properly directed by a magnetic field. Whatever clocks and switching devices are necessary are contained in the box at the center.

The item of greatest doubt, because of weight problems, is the magnet, but it is assumed that it would be a combination permanent and electric magnet. All of the current used could contribute to the magnetic strength, and it might be economical to leak continuously some fraction of the captured electricity to supply part of the magnetic field. The static store of electrons would provide some electrostatic field. It may be determined that the process might be started with help from a storage battery and, from then on indefinitely, be automatic.

# Quantity of Heat Energy Received from the Sun

**By Grandison Gardner**

VOL. 4 1960

**Many of us are interested in finding ways of converting solar energy directly into mechanical or electrical energy, and the author has thought it would be useful to many, particularly to members of the Association for Applied Solar Energy, to have a convenient, even if rough, graph from which such data can be obtained. The author has shown this quantity diagrammatically, averaged over a 24 hour day for three positions of the sun (six dates throughout the year) and for all latitudes. He has also shown his method of integrating and averaging these data.**

**This energy averages about one-half horse power per square yard at latitudes near the declination of the sun, about one-tenth horsepower at the pole in mid-summer, and of course none at the dark pole.**

**The average during the hours of sunshine, except in high latitudes and near mid-summer and mid-winter, is about double the twenty-four hour average, and the night average is none.**

**Although the author's sketches and diagrams are somewhat rough, they show relative values quite well, and they are usable for preliminary and approximate estimation for engineering purposes.**

In a study of the utilization of solar energy, a first question might be: "How much is there?" The radiation pyrometer is one means of getting an approximate measurement of the rate at which radiation from the sun is being received on the surface of the earth, where it is perpendicular to the direction of radiation, and by the vertical column of air above it. If the surface is sloping, a given amount of radiation is distributed over a larger area, and the intensity is correspondingly decreased. The intensity is proportional to the cosine of the angle of slope of the surface away from the perpendicular. At any given time, there is only one point where the surface is perpendicular although half of the earth is always receiving radiation. The average daily intensity of radiation received is computed below for all latitudes and three declination positions of the sun. These values of average intensity are plotted on a

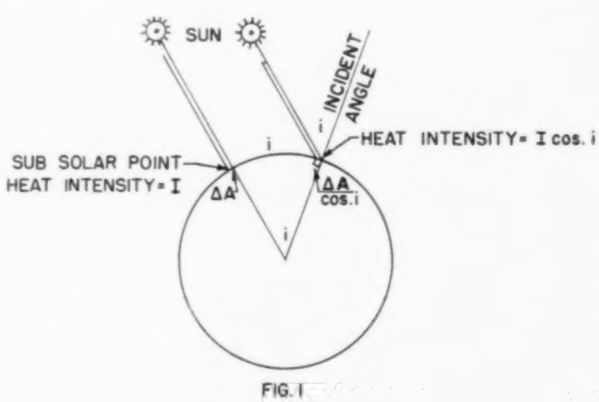


Fig. 1

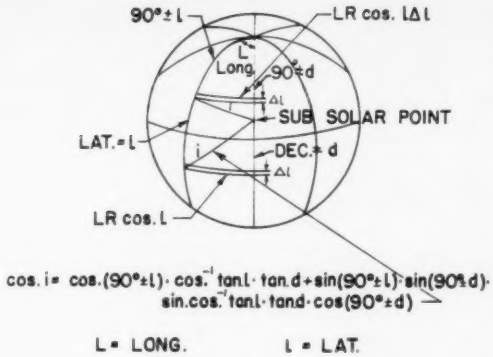


FIG. 2

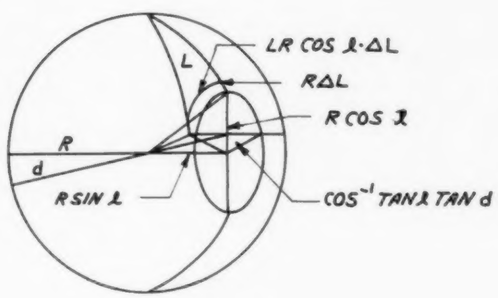


FIG. 3

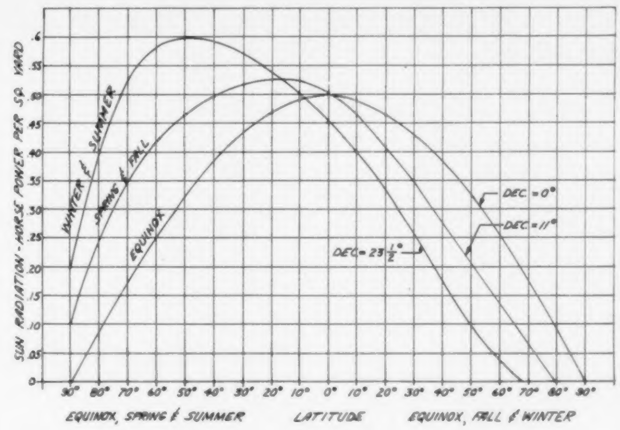


FIG. 4

conventional diagram to show the distributions visually.

This analysis applies only to direct heat energy. There may also be great quantities of unobserved nuclear energy that can be put to use. Part of the heat is absorbed by the atmosphere, and the greater part of that not absorbed by the atmosphere is absorbed by the land and water surface. Some is reflected back into space.

If the intensity of the sun's heat at a point vertically beneath the sun is $I$, the heat intensity at any other point is proportional to $I \cos i$, $i$ being the incident angle and the great circle arc between the point and the sub solar point (see Fig. 1). The sum of the heat that falls on a narrow strip along the latitude parallel through the point is proportional to $I$ times the integral of $R \cos l \cos i \, dL$ (Fig. 2 and 3) over the illuminated arc of the latitude circle. This arc is $2 \cos^{-1} \tan l \tan d$. ($l$ = lat., $L$ = long. and $d$ = Dec.) This sum divided by $2\pi R \cos l$ is the average intensity at this latitude:

$$\int dH = \frac{IR \cos l \, 2}{2\pi R \cos l} \int_0^{\cos^{-1} \tan l \tan d} \cos i \, dL$$

$$= \frac{I}{\pi} \int_0^{\cos^{-1} \tan l \tan d} [\cos (90 \pm d) \cos (90 \pm l) \, dL$$

$$+ \sin (90 \pm d) \sin (90 \pm l) \cos L \, dL]$$

$$H = \frac{l}{\pi} [\cos (90 \pm d) \cos (90 \pm l) \cos^{-1} \tan l \tan d$$

$$+ \sin (90 \pm d) \sin (90 \pm l) \sin \cos^{-1} \tan l \tan d]$$

$\cos^{-1} \tan l \tan d$ must be radians. This will be less than half $\pi$ in the hemisphere opposite the declination. $\pi$ minus these values give integrals for the hemisphere more than half illuminated.

Detail computations of $H$ for one latitude North and one South are included here, and $H$ for all latitudes for declinations 0, 11 and $23\frac{1}{2}°$ is shown graphically in Fig. 4.

$d = 23\frac{1}{2}$. $l = 15$. $90 - d = 66\frac{1}{2}$. $\cos 66\frac{1}{2} = .3985$. ($90 + l = 105$. $90 - l = 75$. $\cos 105 = -.259$. $\cos 75 = .259$)

$\tan l \tan d = .1165$. $\cos^{-1} .1165 = 83.31 = 1.456$ (or 1.686) rad. $.3985 \times (-.259) \times 1.456 = -.1505$. $.3985 \times .259 \times 1.686 = .174$.

$\sin (90 - d) = \sin 66\frac{1}{2} = .918$. $\sin (90 - l) = \sin 75 = .966$. $\sin \cos^{-1} \tan l \tan d = \sin 83.31 = .994$. $.918 \times .966 \times .994 = .880$. $.880 - .1505 = .7295$. $.880 + .174 = 1.054$.

$H$, for 15 lat. of sign same as dec., $= 1.054 \frac{I}{\pi}$;

for opposite sign, $H = .7295 \frac{I}{\pi}$.

For $l = 0$, $\tan d \tan l = 0$, $\cos^{-1} = \frac{\pi}{2}$, $\sin \frac{\pi}{2}$

$$= 1, H = \frac{I}{\pi}. \quad (0 + \sin 66\tfrac{1}{2} \, l^2) = .916 \frac{I}{\pi}.$$

For $l = \pm 66\frac{1}{2}$ and $d = 23\frac{1}{2}$, $\cos (90 - d) = .399$, $\cos (90 - l) = .916$, $\tan l \tan d = 1$, $\cos^{-1} 1 = \begin{cases} \pi \\ 0 \end{cases}$,

$\sin 0 = 0$. $H = .399 \times .916 \times \pi \frac{I}{\pi} = .365 \, I$ or 0

For $l = 90$, $H = \frac{I}{\pi} \cos (90 - d) = .3985 \frac{I}{\pi}$ and

For $l = d,= 1.024 \frac{I}{\pi}$

Hausmann and Slack[1] give the value for $I$ as 0.033 calories per square centimeter per second. $I/\pi$, then, is 0.0105 cal. per sec. per sq. cm. or .044 Joules per sec. per sq. cm. = .044 watts per sq. cm. = .44 kilowatts per sq. meter = .59 horse power per square meter, or roughly half a horsepower per sq. yard.

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# Two Atmospheres

**By Grandison Gardner**


**One needs but to look at a few successive pictures of the corona of the sun to realize what a tremendous quantity of highly dissociated material is being continuously thrown out in all directions by this highly dissociated and explosive mass. Much of this material falls back into the sun, and much escapes with velocities too high to allow interception. Much, however, comes into the earth's gravitational field at speeds that allow the earth to pull individual nuclear and larger particles into elliptical orbits about the earth. This article suggests that such particles travelling in individual orbits form a definite and finite atmosphere—particles of which do not touch the earth—in the region beyond the familiar fluid atmosphere, which rests upon the earth's surface.**

**Rough calculations and one diagram illustrate in some detail what these orbits would be like, and the somewhat liberal approximations, and perhaps even numerical errors, do not lessen the logic or the soundness of the idea.**

**The author computes orbit dimensions by formulae previously used by him in computing ballistic missile trajectories, but they are consistent with what is commonly known as Kepler's law and with conventional geometry.**


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## INTRODUCTION

The purpose of this short paper is not to prove but to suggest the existence of a much more substantial dynamic atmosphere, than is generally visualized, above the thin layer of fluid air lying directly on the surface of the earth.

Because they are so cumbersome, figures and formulae are avoided herein except for the few necessary for illustration. Those used are rough approximations considerably rounded off to numbers that can be set on a slide rule. They should not be used for problems requiring accuracy.

Speeds of particles in circular orbits around the earth and the gravitational attraction of the sun were computed by equating centrifugal force and gravitational attraction, or rather these forces divided by mass:

$$\frac{V_p^2}{R} = G_e \frac{R_e^2}{R^2} \qquad [1]$$

$$\frac{V_e^2}{R} = G_s \frac{R_s^2}{R^2} \qquad [2]$$

$G_e$ is gravitational acceleration at the surface of the earth = 69552 nautical miles per hour per hour, and $G_s$ is the corresponding value for the sun's acceleration constant. $G_s$ = roughly 30 $G_e$. The diameter of the sun, which subtends an angle of 32 minutes, is roughly 110 times that of the earth. $G_s$ is computed for a distance 110 times farther from the sun's center than $G_e$ is measured from the earth's center and is, for this reason, less than some might expect it to be. If the average density of the sun were the same as for the earth $G_s$ would be 110 times $G_e$. Since it is only 30 times as great, the sun's density must be only 30/110 or .273 times that of the earth. The length of the radius of the earth is taken as 3520 nautical miles, and 382,000 nautical miles are used as the radius of the sun. The radius of the earth's orbit is roughly $82 \times 10^6$ nautical miles, and the orbit is assumed to be circular. The radius of the moon's orbit is roughly 210,000 miles, and the orbit is assumed to be circular. $R$ is used generally in the formulae above, and following, as the radial distance to any point on any of various orbits.

Nautical rather than statute miles are used because

they convert directly into minutes of arc on great circles of the earth. Miles, miles per hour, and miles per hour per hour are used rather than the corresponding feet and seconds units, partly because numbers are a little more wieldy and partly because we usually think of such speeds and distances in these units.

Formulae for computing the axes of elliptical orbits and speeds along their arcs (at the points nearest the earth: $V_0$ and $R_0$) are:[1]

$$\text{Length of major axis, } 2a = \frac{I}{-H} \qquad [3]$$

$$\text{Length of minor axis, } 2b = \sqrt{\frac{J^2}{-H}} \qquad [4]$$

$$J^2 = R_0^2 V_0^2 \sin^2 \alpha. \qquad [5]$$

At the initial positions named above, $\sin^2 \alpha = 1$.

$$H = V_0^2 - \frac{I}{R} \quad . \quad I = 2G_e R_e^2 = 1723554.2 \times 10^6.$$

$G_e$ = 69552 (roughly 70,000) nautical miles per hour. [6]

$R_e$ = 3520 nautical miles.

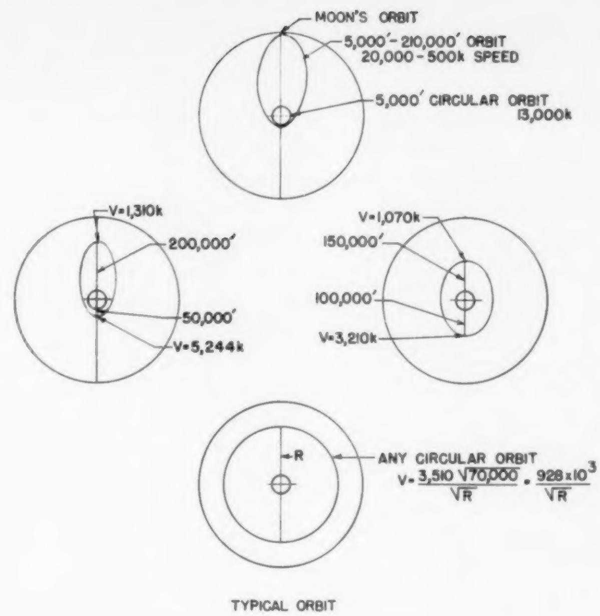


Fig. 1

## DISCUSSION

Aerodynamics engineers, flight research engineers, students of space medicine, meteorologists, and others interested in the atmosphere have been striving, since practical flying began—and before—to define the atmospheric temperature, pressure, density, humidity, thermodynamic characteristics, and other phenomena in mathematical formulae. The first approach has usually been to consider the air a perfect gas behaving in accordance with Charles' law. This is a good approximation within a limited space near the earth's surface and within certain limits of temperature, pressure, density, and humidity. It is quite inadequate, however, for problems of very high altitude flight operations.

There is very probably another atmosphere, of sufficient density to be an important factor in future flight problems, made up of dust particles, large molecules, small molecules, ionized atoms, protons, neutrons, electrons, photons, and other ons, paying little attention to the Charles' law, each particle, at least temporarily, flying in its own orbit about the earth. This dynamic atmosphere would be dominated at altitudes, perhaps below 20 miles, by the atmosphere with which we are more familiar (which we might designate as the fluid atmosphere), but would be dominating at higher altitudes, and there would be a gradual blending of one into the other. There are, without doubt, many such particles surrounding the earth, and it appears that the conclusion is developing (if it is not already the accepted belief) that the mechanism of transfer of heat from the sun to the earth is the projection of a powerful and steady stream of particles of many sizes, travelling with speeds varying from moderate to very high, against the earth and into its atmosphere. Particles projected along straight lines or nearly straight lines connecting the sun with the earth or the denser part of its lower atmosphere would strike the earth or become a part of its atmosphere. Other particles would be pulled into curved paths and strike the atmosphere if not the earth. Others within reach of the earth's gravitational attraction, and not of speeds approaching the speed of light, would be pulled into curved paths and some percentage into elliptical orbits about the earth. Very high speed particles would deviate little from their courses and might drive other particles out of the earth's field as they go by. Some particles travelling on ellipses of very long major axes would get lost due to the earth's change of location in its orbit pending the time the particle might have returned if the earth remained in a fixed position. We can eliminate these long orbits from discussion for convenience (but not forget them) and consider only those orbits confined within a sphere bounded roughly by the moon's orbit. All of these will travel with the earth throughout its annual circuit.

Judging by the rate at which the heat of the sun warms the earth and its atmosphere each day and the

difference between temperatures in the shade and in direct sunlight, we can be sure that the stream of radiated particles may have considerable density and that density of those diverted into the control of the earth over an infinitely long period of time might be considerable, even if only a small fraction of those that come near. To look at a series of current photographs of the sun's corona convinces one that tremendous quantities of highly dissociated material are being thrown off the sun continuously. If they had accumulated since the beginning of the earth's history, the quantity might have grown into a solid mass. The principal losses would be those that fall into the earth's atmosphere after collisions among themselves and those re-energized by very high speed particles and driven beyond the earth's effective field of gravitation. If such losses by collision were few, the density would have, long ago, become very great. If losses are very high, there must be small free space between particles, and this defines a dense medium.

The terms "dense medium," "substantial density," etc., can not mean anything comparable to the air in which we normally live or the air in which our most modern aircraft are flying, but they could mean something to resist very high speed flight and to furnish lift to very fast aerodynamic aircraft. Our artificial satellites have probably already given us some clues as to the meaning of the word "density" in this discussion. In such an atmosphere, there might not be any such thing as compression waves and sound transmission. The concept of heat and temperature out there might be a different one. There would be no humidity and therefore no clouds or local storms. The atmosphere would be uniform over the earth independent of the earth's rotation and independent of latitude.

Since the diameter of the sun is greater than the diameter of the moon's orbit, we might reasonably assume that the density of particles passing into a sphere of diameter equal to that of the moon's orbit (or a disc through the center of this sphere perpendicular to the direction of propagation of particles) would be uniform, except for variations of the sun's surface due to sun spots, etc. However, since those particles attracted into orbits about the earth are again distributed along the perimeters of the orbits, they must be less densely distributed along orbits of long radii. In other words, the density of particles in orbit would be inversely proportional to the square of their radii, or densest nearest the earth.

Another orbital characteristic to be noted is that all orbits, as they are created, cross over or under all the others twice on the straight line that passes through the centers of the sun and the earth, creating two regions of concentration where collisions would be most frequent and where electromagnetic and luminous phenomena might be highest. Since this line moves relatively to the earth along a pair of parallels of latitude on opposite sides of the equator distributing the concentration effects all the way around the earth each day, the effects observed on the earth would not be great. On the side opposite the sun, they might be most noticeable, particularly when the sun is at its extreme position on the opposite side and the line on this side is in an area where darkness predominates.

To better visualize an atmosphere of particles in orbit about the earth, a diagram showing typical orbits is appended. $Vo$ is the speed of a particle as it passes a point where its velocity is perpendicular to the line connecting it with the center of the earth. Every particle that goes by has one such point.

At 5,000 miles from the earth's center (1,480 miles altitude), the speed $Vo$ required for a particle to maintain a circular orbit would be about 13,000 k (knots). At the distance of the moon (about 210,000 nautical miles), $Vo$ would be about 2,000 k. If the initial speed, $Vo$, at 5,000 miles were 20,000 k instead of 13,000 k, the path would be an ellipse with a major axis of 5,000 plus 210,000 miles length, and its most distant arc would be nearly tangent to a sphere of 210,000 miles radius and concentric with the earth. The minimum speed of the particle at this most distant point would be about 500 k. Conversely, all particles flying tangent to this larger sphere with speeds of 500 k would have orbits tangent to the 5,000 miles sphere. All particles flying tangent to the 5,000 miles sphere with speeds between 13,000 k and 20,000 k would have orbits permanently confined in the sphere of 210,000 miles radius. All particles flying tangent to the outer sphere with velocities between 2,000 k and 500 k would have orbits of similar characteristics and be similarly confined, and all of these orbits would remain permanently with the earth. Besides all of these particles, there are others with similar paths tangent to as many pairs of spheres, concentric with the earth and between the larger sphere defined and the earth's fluid atmosphere, as can be imagined.

Although the space is large and the particles are small, the foregoing and the appended diagram are intended to show that the density near the earth may be far from negligible.

Some roughly sketched orbits are shown in accompanying figures. The general formula for speed in a circular orbit (in nautical miles per hour) is: $V = 928000/\sqrt{R}$. Particles entering the system tangent to circles concentric with the earth may have lesser speeds and still form permanent (but elliptical) orbits. In order to be clear of the fluid atmosphere, only orbits whose shortest radii are 4000 miles are considered. In order to continue in orbit, particles must

pass this minimum position with speeds of 14,670 k or higher. By the Kepler law, speed times radius at the minimum point equals speed times radius at the most distant point, so $4000 \times 14{,}670$ is equal to the radius of the reference circle times $V$, and $V = 14{,}670 \times 4000/R$. If the circle tangent to the path of entry were of 8000 miles radius, the slowest entering speed required to form an orbit would be 7,335, etc.

Since we can assume, without proof, that all orbits smaller than that of the moon will be a part of the earth's system and travel in the earth's orbit with the earth, we may also consider speeds higher than that required for a circular orbit but not so high as to orbit beyond the distance to the moon. Using a formula given in a preceding paragraph: $2a = (I/-H)$ and $-H = (I/R) - V_0^2$, we find that

$$V = 1{,}311{,}000 \cdot \sqrt{\frac{1}{R} - \frac{1}{210{,}000 + R}} \qquad [7]$$

If the radius of the circle tangent to the path of entry were 8000 miles, $V$ would be equal to 14,421 k, etc.

This shows that particles (large or small) entering the system tangent to any circle of 8000 miles radius and concentric with the earth, with any speed between 7,335 k and 14,421 k, would have orbits of their own within a sphere bounded by the moon's orbit and outside of a sphere of 8000 miles radius concentric with the earth.

## ADDITIONAL STATISTICAL DATA

Distance to the sun about 82,000,000 nautical miles.

Dimensions of the sun about 110 times those of earth (radius about 382,000 miles).

Density of sun (average) about .273 times that of earth.

Gravitational acceleration due to sun's attraction, at the surface of the sun, about 30 times that of the earth.

Mass of the sun about $110^3 \times .273$ $(34 \times 10^4)$ times mass of earth.

Escape velocity from the sun about 56.3 times that from the earth $= 56.3 \times 22{,}100 = 1{,}250{,}000$ k, about .002 times speed of light.

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# Power Sources For Satellites and Space Vehicles

**Harold A. Zahl and Hans K. Ziegler***

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**Power sources for satellites and space vehicles must be small, light, rugged, reliable for long operational life under the severe environmental conditions of outer space. The environment generated by the operation of the power source must also be compatible with the operation of the instrumentation carried by the space vehicle. Chemical batteries, solar energy converters, and nuclear energy devices appear as the most suitable energy systems. Chemical batteries, having proven their practical capabilities in several earth satellites, provide reliable power for relatively short life and low-power requirements. Solar energy converters with or without storage devices, which also have already practically demonstrated their capabilities in several satellites, will offer high power for operation over at least several years. Nuclear devices under development promise characteristics which may ultimately surpass the capabilities of solar energy converters although for some time both systems may stay in close competition.**

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The usefulness of artificial satellites and space vehicles is greatly dependent on the provision of reliable long-life power sources for the operation of their electrical and electronic equipment. The contrast between the relatively long physical life of the Russian satellites 1957 alpha and beta and their brief periods of electronic life, signified by signal transmission, has forcefully demonstrated this fact. The problem of providing electrical power for remote and inaccessible locations on the surface of the earth is already one of considerable magnitude, wherein equipment weight and size and fuel support and maintenance represent the main factors. In the case of space vehicles the same factors apply in principle. However, all provisions for the entire operational life must be made before the launching, and no subsequent attendance, maintenance, or refueling will be possible—at least for some time to come. In addition, the severe and unique environmental conditions prevailing in outer space require serious consideration.

There are a number of energy sources and power systems which promise or have already proven capabilities for space applications. It might be of interest to briefly review their advantages and disadvantages.

Principally one must distinguish between two fundamentally different categories of energy systems: those which carry within themselves their own source of primary energy and those which take advantage of natural energy sources which exist in the universe.

In the first category—systems which contain their own primary energy sources:

Chemical batteries,
Nuclear energy devices,
Fuel energy devices, and
Mechanical energy storage devices

are the major representatives.

In the second category—systems which make use of natural energy sources:

Solar energy converters

are at present the only type considered.

To compare the adaptability of these power sources for outer space applications, a number of factors must be taken into account. Above all, there is the basic requirement that weight and size are at a premium and that acceleration, vibration, and centrifugal forces associated with the launching and operation of space vehicles call for utmost mechanical rigidity. In addition to these basic requirements come the unique operating conditions which are imposed by the outer space environment. These are:

- Perfect vacuum,
- Loss of gravity—if not replaced by centrifugal forces,
- Temperature extremes which are exclusively determined by radiation balance
- Exposure to high intensity radiation—ultraviolet, x-rays, gamma rays, cosmic rays,
- Exposure to bombardment by high speed particles—meteorites, micro-meteorites.

Although these are the major factors which could interfere with the operation of a power source, one must necessarily also consider what secondary effects the operation of the power source may possibly impose

* This paper, originally presented at the 5th Reunion of the CSAGI in Moscow, USSR, August 1958, has been revised slightly by the authors to reflect the present state of the art. Permission for republication has been granted by the National Academy of Sciences. The original paper is being published in *Annals of the IGY*, Vol. XI, 1960.

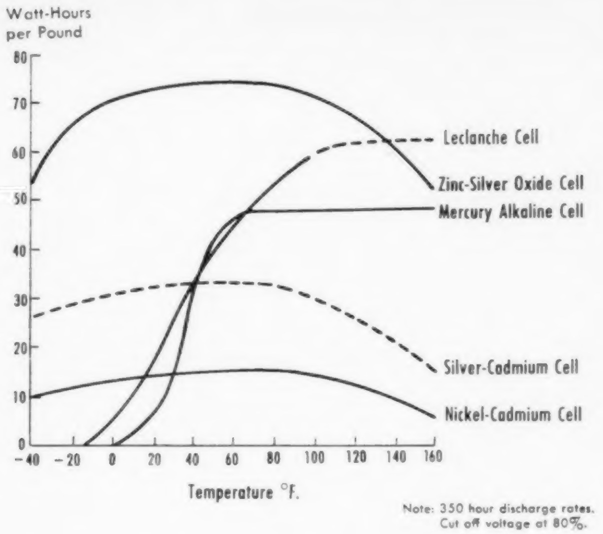


Fig. 1—Watt-hours per pound capabilities of the most important chemical battery systems as function of operating temperature.

on the space vehicles and the equipment carried in it. Among these secondary effects are:

Thermal radiation,

Nuclear radiation,

Disturbance of mechanical equilibrium.

As far as radiation is concerned, both types may require particular attention when life science experiments are conducted.

As for the mechanical disturbances, they could be generated by exhaust of combustion products or motion of parts if not perfectly balanced or by shifting of the center of gravity due to fuel consumption. As consequences of such disturbances, deviations of the space vehicle from its prescribed path or undesirable perturbations could be the result.

Against this background of requirements and restrictions, it is well to compare the various types of energy sources which contain their own supply of prime energy.

Chemical batteries can be built to satisfy the severe mechanical requirements; and although their temperature characteristics are far from ideal, particularly at the low temperature end, space vehicle engineering can provide sufficient temperature control to make satisfactory operation possible. As a matter of fact, chemical batteries in almost a dozen United States satellites have performed perfectly to prediction. The U.S.S.R. satellites contained battery sources, although we do not know if they fulfilled the expectations of their designers. Chemical batteries have no serious handicap in the outer space environment. Sealed constructions resolved the vacuum problem although meteorites of sufficient impact to produce leaks would be a danger. Loss of gravity effects can be overcome by design. There is no noticeable effect caused by high energy radiation. Neither do batteries generate any detrimental secondary effects upon vehicle or equipment. It seems that chemical batteries would be ideal, were it not for their unfavorable weight and size. The best available types of batteries today under optimum operating conditions offer approximately 80 watt hours per pound; or, in other words, one pound of batteries is required for one watt of power for three days of operation. A space vehicle with more elaborate electronic equipment, for instance, with a 5-watt power drain, would call for 550 pounds of batteries for a one-year operation. With present payload limitations for satellites, battery operation is therefore restricted to very low power drains and short life periods.

In connection with the discussion of chemical battery power sources, a word may be in order regarding the so-called "fuel cells" which have been under development for some time. Basically the fuel cell is nothing more than a chemical battery in which the active material, instead of being an integral part of the device itself, is fed into the converter only when power is required. For ground based operations such substitution and the use of a continuous supply of active material may result in very desirable types of long-life chemical batteries. For space vehicle applications, no apparent advantage can be seen since one or the other type of material would have to be carried on board. Recent results indicate, however, that fuel cells may eventually be perfected to offer 500 watts per pound for long time operation, which would place them well above chemical batteries of conventional type. Also regenerative systems have shown promise. No fuel cells for economical use in space applications will however be available for some years.

*Nuclear energy conversion* devices are very promising. Unfortunately, very little hardware is yet on hand to demonstrate conclusively the practical results. The early types of "nuclear batteries" with high voltages and extremely low current drain are of value only in very few special cases. The nuclear-thermoelectric converters, using isotope radiation energy to produce heat and to convert the heat with thermocouples into electrical power, have shown considerable potentialities, and it is expected that operational models of sufficient power output will be available in the very near future. Output ratings of 1000 to 3000 watt hours per pound are expected depending on the isotope—the lower value, for instance, for a cerium 144 source and the higher for a polonium 210 source—and corresponding half-life periods of 290 and 136 days respectively, during which the power output drops to 25%. The

major portion of the system weight will thereby be taken up by the thermoelectric conversion devices.

Even if the quoted weight figures do not include possible necessary shielding, an improvement factor of more than one order of magnitude is indicated compared with chemical batteries. It must, therefore, be kept in mind that these early nuclear devices operate with very low efficiencies, due to the fact that thermocouple conversion is still very inefficient. Considerable improvement should be expected as emphasis is placed on this development.

Nuclear power sources can be built to meet the rigid mechanical requirements; they are not influenced by any outer space environment except that they call for a thermal engineering in which the radiation balance provides high temperature on the hot thermocouple junctions and low temperature on the cold junctions, which may represent occasionally quite a problem. Unfortunately, nuclear sources belong to those which create a secondary environment of thermal and nuclear radiation which cannot be disregarded if the associated equipment is sensitive.

Shielding is then required for the high energy radiation, and enough radiation area must be provided to get rid of the heat. With presently low conversion efficiency, the waste heat is so considerable that the radiation area required for dissipating it into space is comparable to the area which would be required to produce the amount of useful power by just utilizing the solar energy. Nevertheless the nuclear power system of thermoelectric conversion type, and most probably one of the heat engine type, has a very promising future for larger satellites and space vehicles.

*All other fuel type energy* converters using combustion of high-energy liquids or gases are inferior in their watt-hour per pound ratings to the nuclear fuels and are associated with additional operational problems and deserve no serious consideration as space vehicle power sources.

The same verdict is applicable to mechanical energy storage devices like springs, pressurized gases to operate turbines, use of the kinetic energy of the spinning satellite to generate electrical power by means of cutting the magnetic lines of the geomagnetic field, and similar devices. The watt-hour per pound rating in this category is discouragingly low. To mention just one figure: For spring motors it is approximately 0.01 watt hours per pound. In addition the operation of these devices would require consideration of possible disturbance of the mechanical equilibrium of the space vehicle.

This completes the review of the energy systems which contain their own supply of prime energy, and we proceed now to a discussion of those systems which utilize the natural energy available in outer space—*the solar radiation*. Actually, the solar radiation band from the near ultraviolet through infrared appears to be the only worthwhile source of natural energy in outer space which lends itself to profitable utilization. The use of cosmic rays, solar x-rays, and other high intensity radiation, as sometimes suggested, is not advantageous since the energy flux is very low. Of considerable interest, however, could become the utilization of the very long wave infrared radiation, which is the re-radiation from the earth of the absorbed solar energy that is available at all times even when the space vehicle moves in the shadow of the earth. The magnitude, depending on altitude above earth, is up to 20% of the original solar radiation, which is a considerable density. At the present time, however, only the photon and heat effects of the main spectrum area of the sun are available for energy conversion purposes. Some of the details of this power system follow.

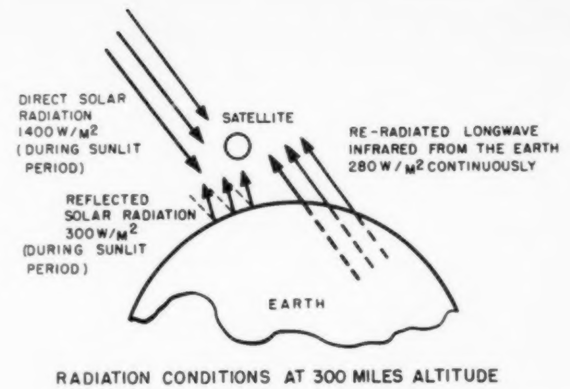


FIG. 2—Radiation conditions at a satellite in 300 miles altitude (reflected and re-radiated value only crude approximation).

The entire solar radiation energy as obtained above the atmospheric envelope of the earth amounts to approximately 1400 watts per square meter for a receiving area oriented at vertical incidence. Needless to say, neither clouds, haze, fog, nor smog ever attenuate this energy offering. However, satellites do usually—and space vehicles may occasionally—enter the shadows of celestial bodies and then be unable to receive the sun's energy. Depending on launching time, orbit altitudes, and orbit inclination, artificial earth satellites may spend not less than 60% of the orbit period in sunshine; and this percentage can be as high as 100% for intervals of weeks. This, of course, has to be considered if the power should be provided continuously; also during the periods of darkness provision must be made for storage of solar energy.

Another important factor requires attention: The

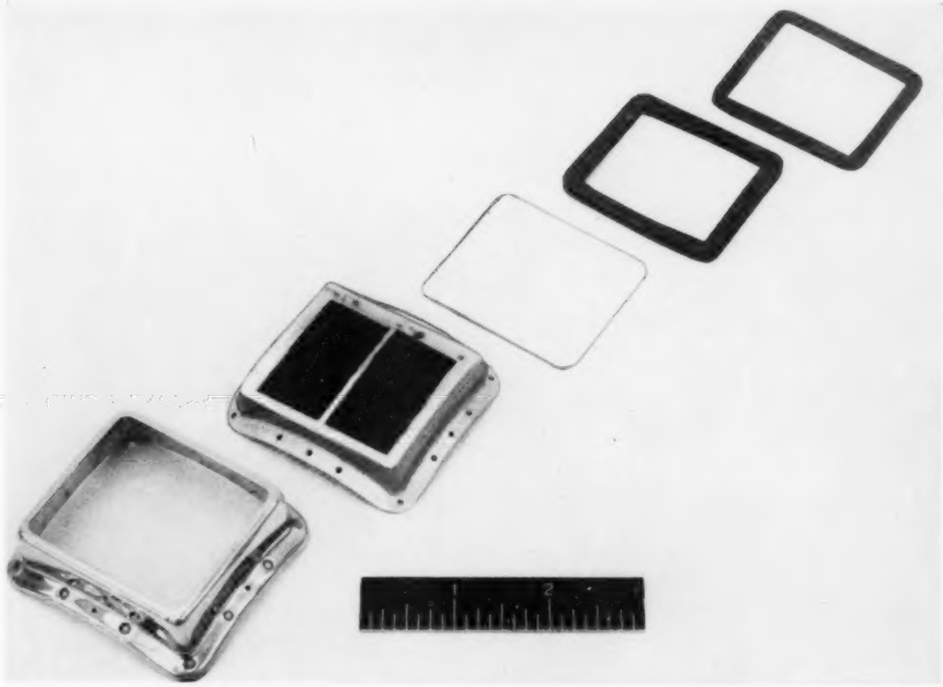

FIG. 3—Parts of the solar cell assembly used in the 6-inch Vanguard satellite.

full amount of solar energy can be received only by receiving areas which are oriented in planes perpendicular to the direction of the sun rays. This would require that the solar energy receiver in a satellite be continuously orientation-controlled, a requirement which can be technically mastered, but which calls for extra weight and power consumption of the stabilizing equipment. One must therefore usually provide the receiving areas for solar energy in such a manner that, for any orientation and anticipated spin and tumbling motion of the satellite, enough projection area is always available. This actually means that several fully rated receiving devices must be provided which share and take turns in accepting the sun's energy. For completely unpredictable orientation, the minimum is four, located in the four planes of an equilateral tetrahedron.

For the conversion of the 1400 watts per square meter of primary solar energy into electrical power, the thermoelectric or the photovoltaic principle could be used if one disregards thermo-mechanic expansion and contraction devices and similar approaches of less attractive weight and efficiency aspects. With present efficiencies of thermocouples and their high weight, also, the thermoelectric conversion principle has not been attractive as yet for satellite use.

The presently employed and well advanced system is that of the photovoltaic converter. The silicon junction cell, originally invented and developed by the Bell Telephone Laboratory, is thereby the basic conversion element. It can be mass produced today with an average conversion efficiency of 10%, and many single elements reach values of 12%. Unfortunately, the full cell efficiency can not be utilized in an integrated solar power system for a satellite. In order to protect the silicon cells from the sandblasting effects

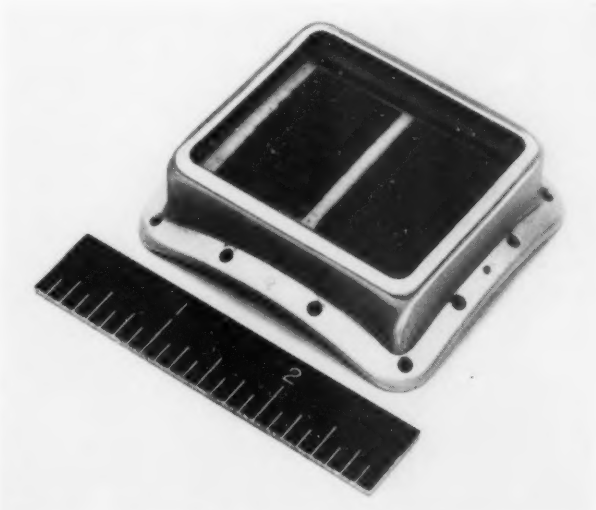

FIG. 4—One of the six complete solar cell assemblies of the 6-inch Vanguard Satellite.

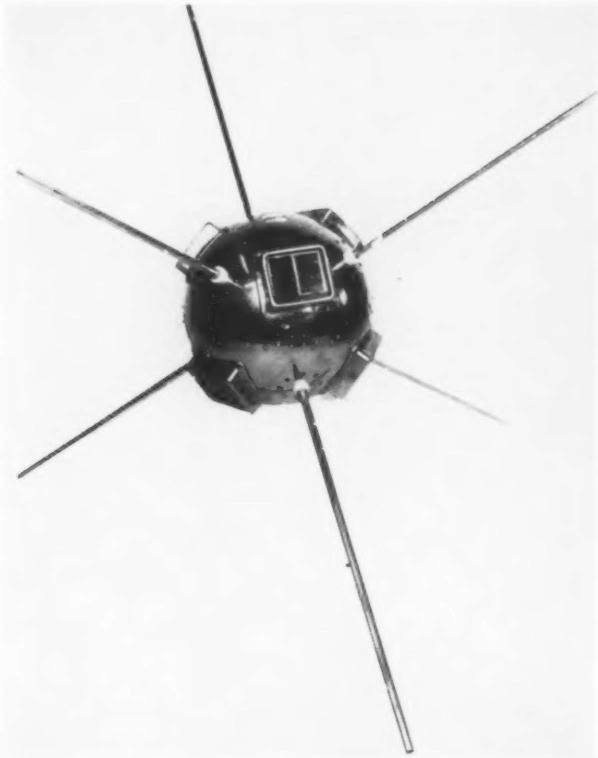

FIG. 5—The first satellite using solar power—Vanguard, 1958 Beta. (Power supply designed and furnished by U. S. Army Signal Research & Development Laboratory.)

of micrometeorites, or at least make an attempt to offset this effect, covers of highly resistant fused silica have been provided which, as they are being sandblasted themselves, reduce the transmitted energy up to 20%. If temperatures above 25°C are encountered at the cells' surface, the quoted efficiencies also reduce by approximately 0.48% per °C. For the Vanguard 6.4 inch satellite, the hottest surface temperature has been measured to be about 75°C, at which temperature the power output of the solar cells decreases by 24%. For unoriented satellites having a number of solar cell receivers, a provision must be made to prevent current flow from the sunlit cells into dark cells by means of diodes, which in turn can cause losses up to 10%. Considering all this, in solar power systems using no storage devices, the overall efficiency of the system will be lower than the original 10% and can be as low as 5%.

The Vanguard TV-4 test satellite, launched on 17 March, was the first satellite ever equipped with a solar power system. Designed and engineered by the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J., this satellite has continuously operated for 2 years already with excellent results.* Since the orbit of this 1958 beta satellite

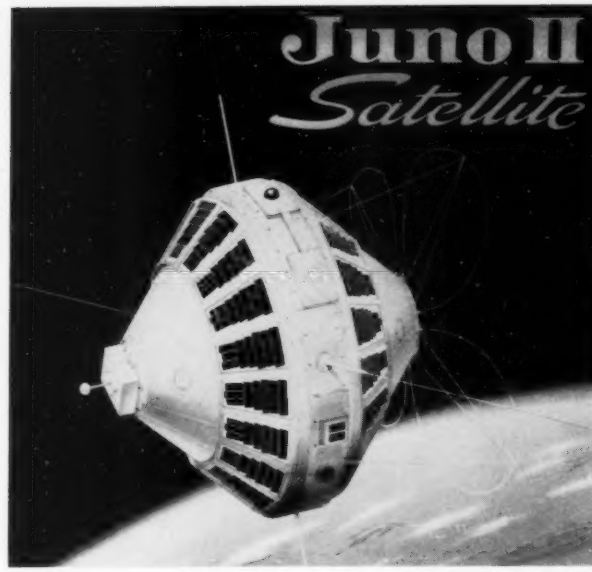


FIG. 6—Explorer VII equipped with solar power supply designed and furnished by the U. S. Army Signal Research & Development Laboratory (JUNO II Satellite).

will be very long lived (200 years has been mentioned recently), this first outer space solar power system may continue to perform for years if the solar cells are not damaged by the environment. The environmental factors which might be detrimental to the silicon cells are: very high temperatures—above 300°C—and strikes by larger meteorites. Damage by high intensity radiation has proven in extensive tests to be of minor influence; and only solar x-rays have some marked effect which, however, seems to require periods of approximately seven years to cause a 25% reduction in power output. All indications are, therefore, that solar conversion devices of the silicon type may have life periods of a number of years. Based on actual engineering figures the weight conditions for solar power sources for satellites, with no storage provided, are as follows:

To produce one-watt power output in an unoriented and uncontrolled satellite 1.7 to 2.2 lbs are required for the range between 25°C and 125°C of surface temperature. With an assumed life of one year and a minimum of 60% sunlit period, this corresponds to 3100–2600 watt hours per pound, which is about the same rating presently achievable with nuclear sources for the same application and could be easily doubled, if the solar cells—as anticipated—prove to have longer life.

If operation on the dark side of the orbit is required, storage batteries must be provided. Investigations continuing over almost four years have indicated that nickel cadmium batteries of hermetically sealed construction are the most suitable storage devices at this time. Due to the fact that in an unattended nickel

* Other satellites, such as Explorer VI, and VII, and also Sputnik III, have since demonstrated the utility of higher rating solar power sources; and many future satellites will be provided with such devices.

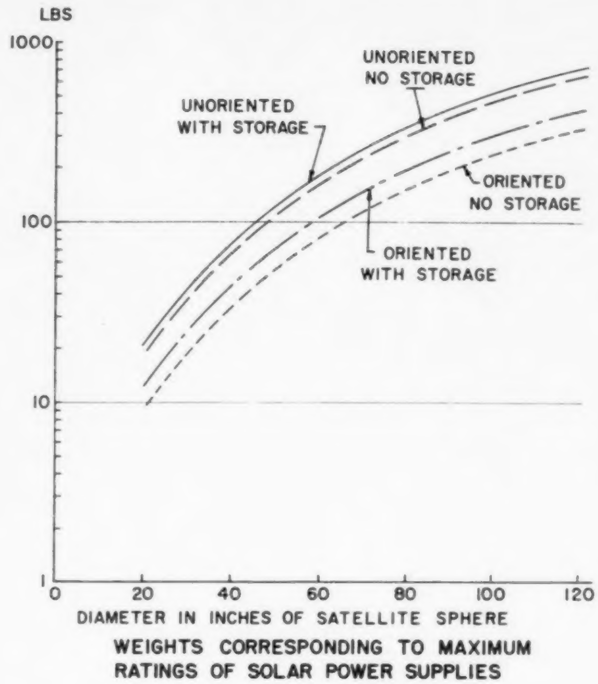


FIG. 7—Maximum solar power ratings obtainable with various sizes of spherical satellites, oriented and unoriented, with and without storage.

cadmium battery a continuous deterioration of the electrolyte takes place with each charge and discharge cycle, these batteries have, however, a limited "long" life. Presently available results point to a life of at least 6000 cycles with hope for possible 11,000 cycles at reasonable battery temperatures. Since each cycle in satellite operation would correspond to *one* orbit, and approximately 10 to 12 orbits per day are expected for satellites with orbit altitudes, life periods of 500 to ultimately 1000 days or $1\frac{1}{2}$ to 3 years seems to be the limit for low orbits—if no new ways of improvement or entirely new storage methods are forthcoming.* In order to provide power storage, the solar energy receiver must, of course, be rated to cover not only the actual load requirement during sunlit periods but in addition the amount of energy to be stored, including storage losses. With sunlit portions of not less than 60% of the orbit, this requirement can be satisfied by doubling the rating of the solar receiver compared with one necessary for a non-storage system. The weight conditions for solar power systems with no orientation control and with storage can be given as follows:

To produce and store 1-watt, between 5.6 and 7.5 lbs are required in the temperature range between 25°C and 125°C. This corresponds for a 1-year life to 1600 to 1200 watt-hours per pound, and for a 2-year life to 3200 to 2400 watt-hours per pound which is competitive with present nuclear devices. Power systems of this category are presently being built and will be used in future satellites.

A graph may illustrate what maximum amounts of solar power can be obtained with present sizes of spherical satellites. A second graph illustrates the corresponding weight requirements. Considerable amounts of power can be had if payloads permit the necessary weight.

In summary, the situation with power sources for satellite and space vehicle applications at this time may be described as follows:

For short time and low power requirements—chemical batteries represent the best solution. *They offer up to 80 watt-hour/lb*, and may go as high as 100 watt-hour/lb.

For long periods of operation in the low, medium, and high-power range, solar conversion systems—with *2600 to 3100 watt-hour/lb* for non-storage type and *1200 to 1600 watt-hour/lb* for storage type for one year or 2400 to 3200 watt-hours/lb for two year operation appear very favorable. These values apply to space vehicles with no orientation control.

Nuclear power devices with presently *1000 to 3000 watt-hour/lb* are expected to improve further and to eventually provide highly reliable sources for medium and high-power and long-life requirements—although competition of solar sources, depending on their long-range behavior and practical reliability, may be quite

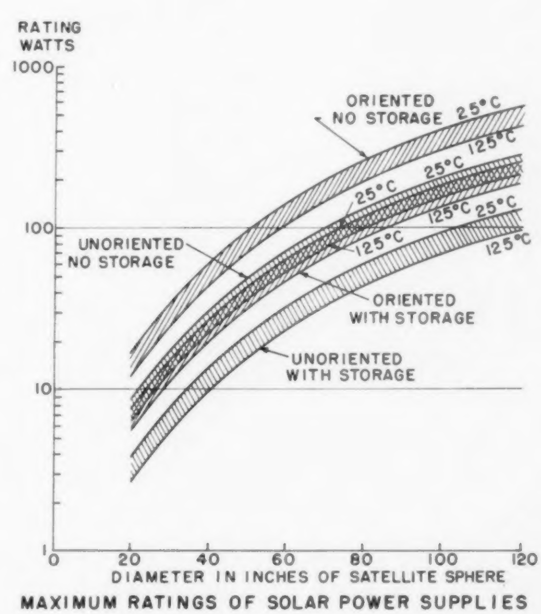


FIG. 8—Weight requirements which correspond to the maximum power ratings as shown in Fig. 7.

* With higher orbits presently planned for various applications, much longer life can be achieved. For a 24 hour satellite, the life would increase to 6000 to 11000 days, corresponding to 16 to 30 years.

close. In this area very little field experience is yet available.

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# A Report on the Utilization of Solar Energy for Refrigeration and Air Conditioning Applications*

**By J. C. Kapur**

Air Conditioning Corporation Pvt. Ltd., Calcutta, India

**India is the first major tropical country which has set out to widen her industrial dimensions. The prevailing wet bulb temperatures in many parts of the country vary between 80–85°F. In this process the scientists and engineers have to face the problem of the heat of the process added to the heat of the atmosphere. This often results in working conditions beyond the limits of human endurance and a considerable drop in productivity of operators. The high wet bulb temperatures rule out the possibility of using evaporative cooling and the high cost of maintenance and operation eliminate the use of air-conditioning with refrigeration. The object of this study is to explore the possibilities of the utilization of solar energy in conjunction with different systems for the dehydration and cooling of air, and to endeavour to establish one which will be most suited under the Indian conditions. An adsorption or absorption system of dehumidification with sensible and evaporative cooling of air appears to show promise.**

## INTRODUCTION

The utilization of solar energy for the purposes of cooling presents some formidable technical and economic problems. Although a number of experimental investigations have been made, the manufacture of commercial units is still in very preliminary stages. Because of the wide-spread availability of cheaper power and the emphasis on heating in climatic control no major organized effort has been made to date in the more highly industrialized countries to tackle the problems of cooling with solar energy.

In India, however, the problems are altogether of a different nature, and can be generally outlined as follows:

(1) Large parts of India are without traditional sources of power, with very little or no hope of any appreciable development in the foreseeable future.

(2) India is the first major tropical country which has set out to widen her industrial dimension, and the losses in productivity due to thermal stresses under conditions far beyond human endurance are well established. Such conditions are becoming increasingly common under the growing industrialization, particularly the establishment of heat-producing industries. The most important deterrent into the use of accepted methods of climate control for purposes of process control and maintaining a high level of productivity are the power and maintenance expenses. The utilization of solar energy, therefore, assumes considerable importance. (For a detailed note see Schedule V).

(3) There is an extensive incidence of solar radiation in most parts of India throughout the year.

(4) An important factor in space cooling with solar energy is the availability of maximum solar radiation where cooling is most needed.

In view of the above and other factors, widespread benefits can accrue from an organized effort in the sphere of space cooling and storage refrigeration with solar energy.

### Scope of Study

In view of the paucity of work carried out in this field anywhere in the world, very little information of practical nature is available. A few studies made in the United States, U.S.S.R., and elsewhere show some promise. This investigation is, therefore, being limited

* My special thanks are due to Prof. M. S. Thacker, Director General of Scientific Research in India, for making this publication possible.

**SCHEDULE I**

**Outside Ambient Conditions, Inside Design Conditions, and Load Conditions Under Which the Comparisons Have Been Made Under Schedule II**

| | Alternative A | Alternative B |
|---|---|---|
| *Outside conditions:* | | |
| Dry-bulb temperature | 100°F | 110°F |
| Wet-bulb temperature | 84°F | 70°F |
| Dewpoint temperature | 79.3 | 46 |
| Relative humidity | 51% | 11% |
| Water on cooling tower | 98°F | 85°F |
| Water off cooling tower | 90°F | 77°F |
| *Inside design conditions:* | | |
| Dry-bulb temperature | 80°F | 80°F |
| Wet-bulb temperature | 67°F | 67°F |
| Relative humidity | 50% | 50% |
| Dewpoint | 60 | 60 |
| Effective temperature | 72 | 72 |
| Total load | 60,000 | 60,000 |
| Estimated sensible load | 40,000 | 53,000 |
| Latent load | 20,000 | 7,000 |
| Latent heat/total heat | 33% | 13.0% |
| Total air quantity | 2,500 | 2,500 |
| Fresh air quantity | 400 | 2,500 |
| Recirculated air quantity | 2,100 | |

to a theoretical consideration of the problems involved, particularly from the point of view of the Indian conditions, and to an endeavor to eliminate all those considerations which are not of any practical significance.

As a first step, a comparison has been made between the various types of equipment now employed for the purpose of temperature and humidity control, the sources of power used, and the comparative efficiency of these systems (Schedule I and II).

As a second step, a detailed investigation has been carried out with regard to the over-all efficiency of a system which shows the greatest promise under varying ambient dry and wet bulb temperature conditions (Schedule III and IV).

Similarly, the reflector surface required under varying conditions of solar radiation and sun hours has been estimated.

## Investigation

The most commonly used systems of refrigeration are:

(1) The conventional vapor compression system of refrigeration using electric power.

(2) Absorption system of refrigeration using electricity, gas, kerosene, etc., as the source of power.

(3) Steam jet refrigeration.

(4) Chemical absorption and adsorption method of humidity control, using electricity, steam, gas, or any other source of direct heat.

Item (1) above, though the most efficient system of refrigeration, will require many energy transformations

**SCHEDULE II**

**Analysis of Power Requirements For The Air Conditioning of a House Having Approximately 12,000 cu ft Volume Using Different Systems of Refrigeration**

| System of refrigeration | (1) Source of power for the compressor generator or the regeneration of the chemical desicents | (2) Heat extracted by the system | | (3) Power required for the compressor generator or the regeneration process | | | (4) Gallons of water per hour for the condenser or after-cooler in the chemical dehumidification process | (5) Power for the cooling and recirculation of condenser water (electric) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *Btu/hr* | *kcal/hr* | *kw/hr* | *Btu/hr* | *kcal/hr* | *gal/hr* | *Watts/hr* | *Btu/hr* | *kcal/hr* |
| **A: Conditions Under Alternative A Schedule I** | | | | | | | | | | |
| (i) Vapour compression | Electricity | 60,000 | 15,000 | 5.36 | 18,200 | 4,600 | 1,000 | 1,000 | 3,400 | 860 |
| (ii) Absorption | Gas, electricity, kerosene, solar | 60,000 | 15,000 | | 112,000 | 28,000 | 1,100 | 1,100 | 3,740 | 946 |
| (iii) Steam jet | Steam | 60,000 | 15,000 | | 175,000 | 44,000 | 2,250 | 2,000 | 6,800 | 1,720 |
| (iv) Dehydration or over-dehydration through chemical adsorption or absorption, after cooling and evaporative cooling | Steam, electricity, gas or solar | 60,000 | 15,000 | | *170,000 | 43,000 | 550 | 600 | 2,040 | 516 |
| **B: As per Conditions Stipulated Under Alternative B Schedule I** | | | | | | | | | | |
| (i) Vapour compression | Electricity | 60,000 | 15,000 | 5.00 | 17,000 | 4,250 | 1,000 | 1,000 | 3,400 | 860 |
| (ii) Absorption | Gas, electricity, kerosene, solar | 60,000 | 15,000 | | 112,000 | 28,000 | 1,100 | 1,100 | 3,740 | 946 |
| (iii) Steam jet | Steam | 60,000 | 15,000 | | 175,000 | 44,000 | 1,200 | 2,000 | 6,800 | 1,720 |
| (iv) Dehydration or over-dehydration through chemical adsorption or absorption, after cooling and evaporative cooling | Steam, electricity, gas or solar | 60,000 | 15,000 | | †30,000 | 7,500 | 550 | 600 | 2,040 | 516 |

| | (6) Total power for the refrigeration cycle (3) + (5) | | (7) Over all efficiency refrigeration (2)/(6) | (8) Electric power for the aircooling, filtration, and distributive cycle and controls | | | (9) Total power (6) plus (8) | |
|---|---|---|---|---|---|---|---|---|
| | *Btu/hr* | *kcal/hr* | *Per cent* | *Watts/hr* | *Btu/hr* | *kcal/hr* | *Btu/hr* | *kcal/hr* |
| **A: Conditions Under Alternative A Schedule I** | | | | | | | | |
| (i) Vapour compression | 21,600 | 5,460 | 290 | 900 | 3,100 | 770 | 24,700 | 6,230 |
| (ii) Absorption | 115,740 | 28,946 | 52 | 900 | 3,100 | 770 | 118,840 | 29,716 |
| (iii) Steam jet | 181,800 | 46,000 | 32.5 | 900 | 3,100 | 770 | 184,900 | 46,770 |
| (iv) Dehydration or over-dehydration through chemical adsorption or absorption, after cooling and evaporative cooling | 172,040 | 43,516 | 35 | 1,000 | 3,412 | 860 | 175,452 | 44,376 |
| **B: As Per Conditions Stipulated Under Alternative B Schedule I** | | | | | | | | |
| (i) Vapour compression | 20,400 | 5,110 | 295 | 900 | 3,100 | 770 | 23,500 | 5,880 |
| (ii) Absorption | 115,740 | 28,946 | 52 | 900 | 3,100 | 770 | 118,840 | 29,716 |
| (iii) Steam jet | 181,800 | 46,000 | 32.5 | 900 | 3,100 | 770 | 184,900 | 46,770 |
| (iv) Dehydration or over-dehydration through chemical adsorption or absorption after cooling and evaporative cooling | 32,040 | 8,050 | 178 | 1,000 | 3,142 | 860 | 35,182 | 8,910 |

* See the cycle on the psychromatic chart in Schedule III.

† Actual extraction of latent heat is much smaller than these figures. This is the actual heat required in the regeneration process.

if solar energy is to be used as a source of power. Its economy is closely linked with the economics of electric power generation with solar energy and is, therefore, outside the scope of this discussion. Similar considerations, though to lesser extent, are applicable to item (3), i.e., steam jet refrigeration.

The study of the utilization of solar energy is, therefore, confined to a consideration of systems (2) and (4) above, as follows:

I (a) The absorption system of refrigeration in its application to temperature and humidity control.

(b) The absorption system in its application to equipment such as domestic refrigerator and food storage.

II (a) The chemical absorption and adsorption method for the control of humidity alone.

(b) The evaporative or adiabatic cooling of dehydrated air to obtain comfort conditions.

## TEMPERATURE AND HUMIDITY CONTROL FOR COMFORT WITHIN THE COMFORT ZONE

For the purposes of comparison, a house having a floor area of approximately 1,200 sq ft and a volume of 12,000 cu ft has been selected. The outside ambient conditions are indicated under Alternatives A and B of Schedule I at the end of the report. Alternative A represents a normal peak summer condition for a hot and humid place like Calcutta. Alternative B represents a normal peak summer condition of a hot and dry area like Delhi. For the purposes of this study, most of the other conditions may be assumed to fall within these two extremes.

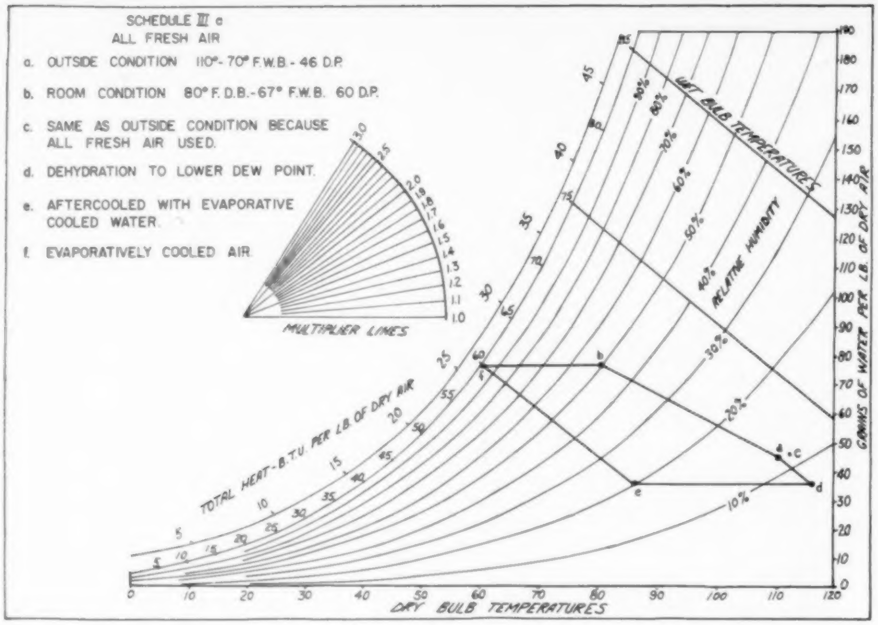
Schedule II indicates the power requirements if the house were to be air-conditioned using different systems of refrigeration under the ambient conditions shown under Alternatives A and B of Schedule I.

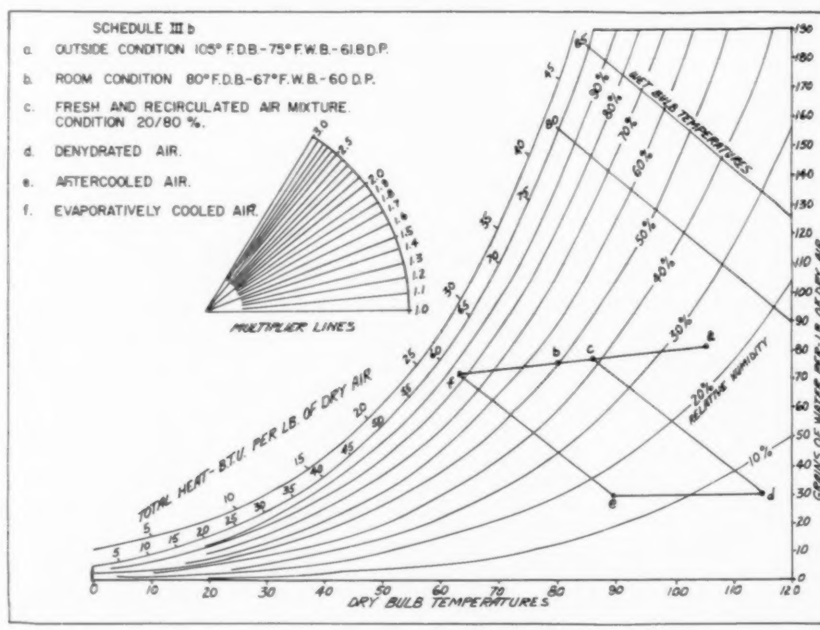
System 1 employs a normal vapor compression unit using one of the Freon group of refrigerants. It uses a shell-and-tube type of condenser and a forced-draft evaporative water cooling tower. The indicated quantities of cooled water are circulated through the condenser every hour. The air-cooling circuit consists of a direct expansion finned heat exchanger, filters and air blower, and an air bypass arrangement.

System 2 employs the absorption refrigeration system with lithium bromide as the absorbent and water as the refrigerant. The unit operates under a high vacuum. The air is cooled, dehumidified and filtered, and supplied to the conditioned space as above.

System 3 employs high pressure steam in a steam-jet refrigeration system, and the water thus cooled is passed through a water-chilled, finned heat exchanger to cool the air, which is, as above, supplied to the conditioned space.

System 4 works on the principle of lowering the dew point of a mixture of 80 per cent recirculated and 20 per cent fresh air (all fresh air in case of Alternative B), which passes through solid or liquid adsorbents or absorbents,

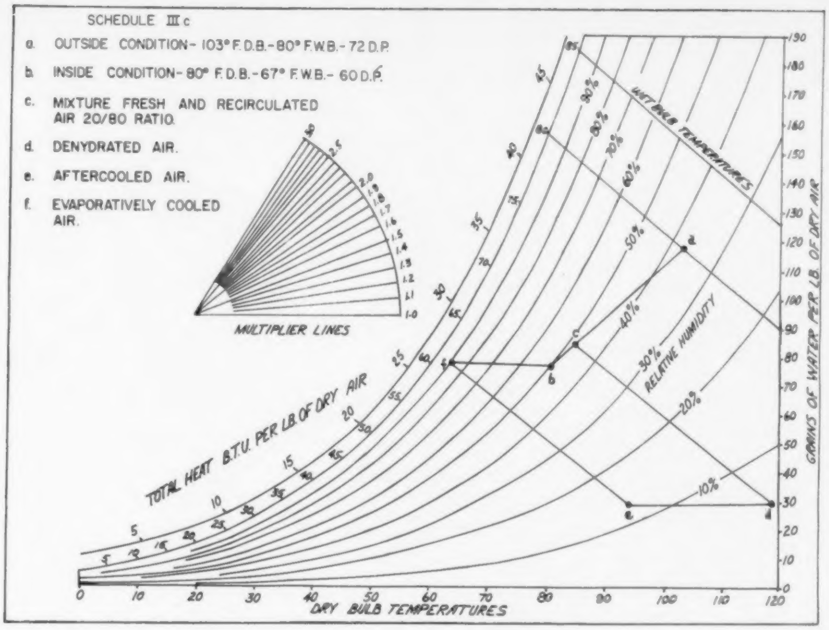


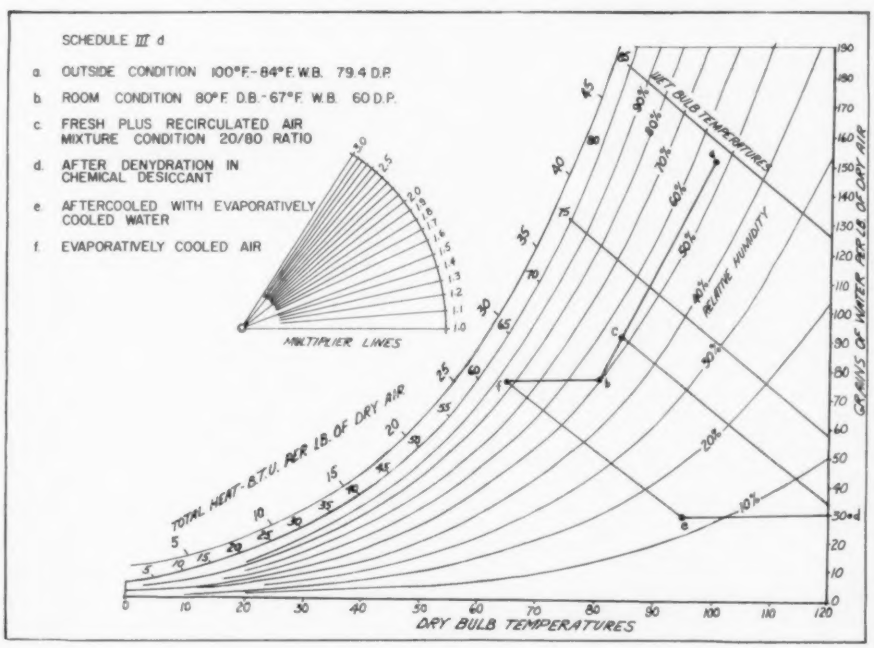






by the extraction of moisture to a predetermined point. The latent heat of the moisture so extracted becomes the sensible heat of the air, and this high temperature air is then passed through a finned heat exchanger wherein evaporatively cooled water (in a forced draft cooling tower) is circulated. By lowering the air to a dew point temperature of about 30° and then cooling by the above method, wet-bulb temperatures as low as 60–61°F can be obtained. Predetermined quantities of water can then be evaporated in the air stream, and it can be supplied to the room in a saturated or semi-saturated condition to maintain the desired conditions in the house.

The excess moisture can be removed by the regeneration of the sorbent at a temperature of 300–600°F. The actual regeneration heat is far in excess of the latent heat released in the dehydration and dilution process. (Among the commonly known solid adsorbents are alumina, silica gel, and activated bauxite; absorbents include calcium chloride (solid) and the liquid absorbents such as lithium chloride, calcium chloride, lithium bromide, or ethylene glycol).




## DATA FROM SCHEDULE II

(1) The vapour compression system has the highest efficiency, about 6 to 10 times that of any other system, but the only source of power that can be used is electricity; hence it is ruled out from the point of view of this discussion.

(2) The steam-jet system works with high pressure steam as the motive power. It is the least efficient, particularly in smaller units, and requires large quantities of water. It is, therefore, ruled out for the purposes of this discussion.

(3) The absorption system of refrigeration and also the adsorption and absorption system of chemical dehydration of air have a wide choice of motive powers, and the transfer of solar energy for the purposes of regeneration should be relatively simpler.

Column (2) of this schedule shows the actual re-

frigeration effect in Btu per hour or kcal per hour and equals approximately five tons of refrigeration (approximated for the purposes of comparison).

Column (3) indicates power required by the compressor-generator in the case of the absorption system, the motive steam for the booster ejector in case of steam-jet refrigeration, and for the regeneration process in the case of absorption and adsorption dehydration. The figures are based on actual computation and verified against actual manufacturers' data wherever available.

Column (4) indicates gallons of water required. In the case of the chemical dehydration system (Subsection (4) of Alternative A) this is the quantity of water which passes through the finned heat exchanger to extract sensible heat from the air after it has passed through the absorbent chamber marked (d) on the four psychromatic charts in Schedule III.

Column (5) indicates approximate power required for the cooling and recirculation of the condenser water, i.e., pump and fan of cooling tower and circulation through the condenser.

Column (6) shows figures for the approximate power for air circulation through the system and distribution to the conditioned area.

## COMPARISON OF RESULTS OF ALTERNATIVES A AND B

An examination of the Column (3) under Alternatives A and B would indicate that there is not much difference in the power requirements under Subsections (1), (2), and (3) of both the alternatives. In actual practice, there will be some variation, but for the purposes of this comparison the variations have either been adjusted or neglected, as they are not of much significance.

An examination of Subsection (4), Column 3, of both the alternatives would, however, indicate that while 170,000 Btu per hour (43,000 kcal per hour) are required to maintain conditions within the comfort zone in the case of Alternative A, with the outside air at a dewpoint of 79.3° and 152 grains per lb of dry air, only 30,000 Btu per hour (7,500 kcal per hour) would be required to maintain identical conditions under Alternative B, when the outside dewpoint temperature is 46° and there are only 46 grains per lb of dry air, although the dry bulb temperature is 110°F.

From the above, it is apparent that the absorption system of refrigeration and adsorption or absorption system of chemical dehydration through desiccants offer the greatest scope for investigation. Under Alternative A the former is more economical; under Alternative B the latter offers considerably higher economy.

The equipment and techniques required for the adsorption and absorption processes of chemical dehydration are developed to a much greater degree, and this method, coupled with evaporative and sensible cooling without refrigeration, can give near comfort conditions in most parts of India, even during the period when solar heat is not at its maximum. Therefore, detailed investigation is being confined to this system.

In Schedule IV has been computed the energy requirements, cooling efficiency, and the reflector area required for refrigeration ambient conditions in different parts of India.

As will be noticed with the increasing outside dewpoint temperature, the requirements of solar heat for regeneration increases considerably, and the system cooling efficiency drops from 200 per cent to 35 per cent.

The possible effectiveness of solar heating during regeneration (Column (6), Schedule IV) has been taken as 30 per cent. These are the results generally realized in some of the recent experiments. It can, however, be stated that the materials and techniques now under development may enhance this effectiveness to as much as 90 per cent, thus reducing the reflector area to almost one-third of the stated figures.

## CONCLUSIONS

(1) A system using absorption or adsorption methods of dehumidification with chemical desiccants shows considerable promise, particularly when it is used in conjunction with sensible cooling (with well or evaporatively cooled water) in a heat exchanger. In the final stage, the air is evaporatively cooled in a controlled manner. Even on a cloudy day, when very little or no dehumidification with the chemical desiccants is possible, reasonably acceptable conditions can be obtained so long as the wet-bulb temperature does not go beyond 75°F, and only sensible and evaporative cooling of the air are used. The availability of solar heat can further improve these conditions. Schedule VI indicates the percentage of time the wet-bulb temperature stays at or below the indicated figure in different parts of India. Taking, for instance, the case of New Delhi during the summer months of March to September, approximately 58 per cent of the total time it would be possible to maintain reasonable conditions even when solar radiation is not available. Except for the rainy or cloudy days, during the remaining period, comfort or close to comfort condition could be obtained almost 90 per cent of the total time.

(2) The reflector surfaces required for dewpoints above 62° go beyond the practical limits, because of the very low effectiveness of solar heating. Widespread

## SCHEDULE IV

**Over-all Performance Efficiency and Solar Reflector Surface under Varying Atmospheric Conditions in Different Parts of India When Adsorbent or Absorbent Chemical Desiccants are Used to Maintain Comfort Conditions**

| Schedule reference | (1) Outside ambient conditions | | | (2) Comfort conditions maintained within conditioned space | | | | (3) Heat to be extracted from conditioned space | | (4) Heat required for the process of regeneration of absorbent or adsorbent | | (5) System cooling efficiency | (6)* Possible effectiveness of solar heating during regeneration | (7) Over-all performance efficiency (5) × (6) | (8)† Actual solar and sky radiation figures, assumed $Q$ in gm-cal/cm²/day | (9)† Mean daily actual hours of bright sunshine | (10) Estimated reflector surface based on information under columns (8) & (9) | (11)‡ Estimated Btu/day/sq ft of collector area |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *D. B.* (°*F*) | *W. B.* (°*F*) | *D. P.* | *D. B.* (°*F*) | *W. B.* (°*F*) | *D. P.* | *R. H.* (%) | *Btu/hr* | *kcal/hr* | *Btu/hr* | *kcal/hr* | % | | % | | | *sq ft* | |
| (a) | 110 | 70 | 46 | 80 | 67 | 60 | 50 | 60,000 | 15,000 | 30,000 | 7,550 | 200 | 0.30 | 60 | 610 | 9.2 | 400 | 690 |
| (b) | 105 | 75 | 61.8 | 80 | 67 | 60 | 50 | 60,000 | 15,000 | 104,000 | 26,200 | 57 | 0.30 | 25 | 581 | 7.9 | 1,250 | 660 |
| (c) | 103 | 80 | 72 | 80 | 67 | 60 | 50 | 60,000 | 15,000 | 150,000 | 37,500 | 40 | 0.30 | 16.2 | 626 | 9.3 | 2,000 | 700 |
| (d) | 100 | 84 | 79.4 | 80 | 67 | 60 | 50 | 60,000 | 15,000 | 170,000 | 43,000 | 35 | 0.30 | 12.5 | 682 | 8.7 | 2,000 | 680 |

* Observed figures on some of the identical U.S. experiments.
† L. A. Ramdas and S. Yegnanarayanan computation.
‡ As compared with an actual U.S. experimental figure of 600 Btu/sq ft collector area.

applications in high humidity areas will have to await development of high-efficiency heat transfer surfaces.

(3) From the experiments with thermal stresses in industrial operations, it is concluded that human productivity drops considerably beyond effective temperatures of 95°. One of the most important deterrents to the utilization of scientific climate control is the cost of operation of such plants. The utilization of solar energy to improve marginal conditions beyond human endurance, used in conjunction with other sources of power for the regeneration process during the periods of nonavailability of solar radiation, can considerably improve working conditions in some of the important Indian industries, such as mining, textiles, foundries, iron and steel, etc. In a recent experiment with a lithium chloride system in conditioning hot and humid air from a dewpoint of 83.5° to 67°, thermal efficiencies as high as 130 per cent have been obtained. Therefore, widespread benefits may be realized through more exhaustive studies.

(4) An attempt to reach acceptable conditions economically may be considerably more practical at this stage of development, rather than to aim for the ideal conditions within the comfort zone. (See Schedule VII for comfort zone.)

## SCHEDULE V

**The Conditions for Human Comfort—Their Application to Industry**

One of the most commonly discussed subjects of all times is the weather. We talk about it when the extremes of climate make life unbearable. We also talk about it when conditions are pleasant and conducive to comfort. Before we can examine the conditions which are most acceptable to the human body and make us completely oblivious to the climate, it is necessary for us to know the manner in which the human body reacts to heat and cold and how heat and cold influence our capacity for work.

The human body is equipped with an important mechanism in its defence against heat and cold. The first and most important item is a dual temperature control located in the brain. This nerve centre is set to keep our internal body temperature at 98.6°F. Sometimes there are slight changes in the settings to 97° in the morning and as much as 99° in the evening. The other function which this thermostat performs is to regulate the skin temperature. Unlike the internal body temperature, the skin temperature varies systematically under normally comfortable conditions. When comfortable our skin area of some 20 sq ft has an average temperature of 92° F. When we talk of comfort in respect to heat, what we are really saying is that our skin is at the right temperature.

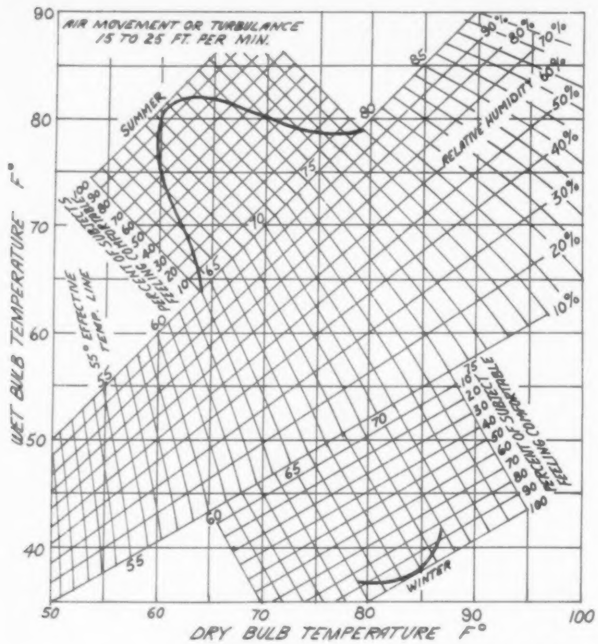
The dual thermostat, therefore, performs the double function of maintaining internal body temperature at 98.6° and keeping the skin temperature near 92°F.

Now we know that for an average undressed person resting in still air within a temperature range of 80°–85°F, the body has to make no effort whatsoever to maintain its heat balance, or, in other words, he is comfortable. If on the other hand he is clothed or active, this comfort range is considerably lower. We can, therefore, term this range as a *neutral* point where the body is neither too hot nor too cold.

Such ideal conditions existed only in our dreams. As the laws of a present-day civilized society do not permit us to remain undressed, we cannot afford to ignore the insulating value of approximately 10°F temperature difference of the average suit of clothing worn in India. Nor can we ignore the normal human body heat production of about 100 watts per hour. Heat always travels from a hotter to a colder body. The total heat of our body depends on the inflow of 100 watts per hour that the body generates and the outflow resulting from the temperature of the surrounding air. Now the first of the climate defense tools is the amount of blood circulating very near the surface of the skin. If the temperature becomes too low, millions of blood vessels near the skin surface close down and provide us with a bloodless layer of tissues with an insulating value approximately equal to that of ½-in. thick cork board.

If, on the other hand, the temperature becomes too hot, the blood vessels in the skin dilate and the blood moves rapidly. In many instances more than half the blood that is pumped by the heart goes directly to the skin and short circuits the brain and other vital organs. That is why on hot days our heart is under a great strain, and our mental function tends to be depressed.

All goes well so long as the air temperatures do not reach the body temperature of 98–99°, but long before this happens the thermostat calls into operation another defense mechanism, the sweat secretion and the body evaporative system. By evaporating large quantities of sweat from the skin sur-




A.S.H.A.E. COMFORT CHART FOR STILL AIR

face the body may hold skin surface temperatures near 95° even in outside atmospheric temperature of 140–150°F, provided humidity is low and evaporation is possible. With the increase in humidity to 100 per cent (which often happens in Calcutta) the tolerance of the air temperature drops from roughly 150° to 90°F. Therefore, the humidity or the moisture content of the air, while not directly affecting the comfort or discomfort of human beings, does so indirectly by making the important mechanism of sweat evaporation inefficient.

One of the most welcome things on a hot and sultry day is a breeze. The motion of air makes the uncomfortable conditions of temperature and humidity more bearable by taking away the sweat-saturated air from our body.

Other important irritants to comfort are dust, smoke, and fumes. It has now been established beyond doubt that the quality of air is equally important.

When it was known that human comfort was linked with so many different elements as temperature, relative humidity, air motion, and even the quality of air and the radiation to cold or from warm surfaces, it became necessary to correlate and evaluate these different factors. The only index that could be developed was based on the combination of temperature, humidity, and air motion which would induce a certain feeling of warmth in a normal human being. This index is known as an *effective temperature*. The value of this index for a given condition of air is fixed by a temperature of slow moving (15–25 ft per minute), saturated air which induces a like sensation of warmth or cold. Thus, an air-conditioning system has an effective temperature of 70° when it induces the same sensation of warmth that is experienced in slow moving air saturated with moisture at 70°F.

During recent years various studies have been conducted by research organizations in the United States and elsewhere in which normal human beings were subjected to various combinations of temperature, humidity, and air motion to establish equivalent sensations of cold and warmth. It has been concluded that in summer about 98 per cent of the people feel comfortable at an effective temperature of 71° (equivalent to dry-bulb temperatures of 72° to 78°F with simultaneous relative humidity of 30 to 70 per cent.) Higher humidity is acceptable at lower temperatures. It has also been concluded that women generally prefer an effective temperature 1° higher than men.

Taking a group of varied individuals in different parts of the world, the summer comfort zone was found to vary within a temperature range from 69° to 73° (dry-bulb temperature 72° to 82° F with humidities from 20 to 75 per cent). The Indian studies indicate the zone to be closer to the upper limit.

In studies by the American Society of Heating, Ventilating and Air-Conditioning Engineers, workers were subjected to high temperature stresses while performing physical or mental labor. It was established that a normal human being is capable of performing maximum mental or physical labor at an effective temperature of 70° (dry-bulb temperatures 74° to 77°F, relative humidity 30 to 70 per cent). The output drops gradually to almost 50 per cent at an effective temperature of 95° (110°F dry-bulb temperature, 92°F wet-bulb temperature, 50 per cent relative humidity). The drop is still more rapid above an effective temperature of 100° (dry-bulb temperature 110°, wet-bulb 98°F, relative humidity 64 per cent).

From the studies of J. B. Haldane fifty years ago to the more recent studies by the British Naval Research Organization, studies in the African mines, and at the U. S. Armed Forces Medical Research Laboratory, the upper limit of collapse due to thermal stresses is placed at effective temperatures between 93 to 95° with air moving at a velocity of 100 to 200 ft per minute. The tolerable effective temperature limit further lowers it if there is no air motion.

Some years ago investigations were carried out with workers in Kolar Gold Field. Recently some of the Indian army scientists investigated the effect of high temperatures on Indian army personnel. In the year 1955–56, under the joint sponsorship of the Ministry of Labour and Health of the Government of India, investigations were carried out on the thermal stresses in the textile industry at the Ahmedabad Textile Industries Research Association. Indian scientists and engineers subjected workers in different age groups to controlled climatic conditions. Within the limits of the investigation, the results of these studies follow a similar pattern to that in other countries, although the upper limit of thermal collapse, though inconclusive, appears to be slightly higher in the case of workers in India.

The effects of frequent and continued exposure of workers to unbearably hot conditions are now well known. The most common ones are the increase in incidence of accident, the lowering of defense against infection, and the resultant increase in the mortality rate.

Most of the investigations carried out so far, whether in the textile industry, jute industry, or in mines, clearly indicate that conditions are far from satisfactory. No doubt the requirements of heat- or humidity-producing equipment from the process point of view in some of these industries make the conditions all the more critical. Yet within the limits of economy there is a considerable scope for reducing thermal stresses on workers and increasing productivity. Only more detailed information (not available at present) will make statutory regulation possible.

In the processes of modern industrialization—whether it is the development of mining, the manufacture of steel, fertilizers, glass, pottery, textile, and jute, or the generation of nuclear power—the dissipation of large quantities of heat, generated during production or added through process requirements, has always been a problem of considerable importance in industrialized countries of the West. But the problems of heat assume a far greater magnitude in the industrialization of a major tropical country like India, especially when we have so little to draw upon in our special problems of the heat in industry plus the heat in atmosphere. Furthermore, the process of the extraction of heat is much more complicated and expensive than that of the addition usually required in colder countries.

Therefore, to keep thermal stresses in the widening dimensions of Indian industry within the range of maximum productivity will require the ultimate in equipment, technique, and ever-growing sources of cheaper power. It is not a utopian dream, but certainly the work of a lifetime for the Indian scientists and engineers of human comfort and productivity.

**SCHEDULE VI**

**Percentage of the Time That Conditions Stayed at or Below the Wet-Bulb Temperatures Indicated (Mar.–Sept.)**

| Wet bulb (°F) | 80 | 75 | 70 | 65 | 60 | 55 |
|---|---|---|---|---|---|---|
| *Bombay* | | | | | | |
| 1953 | 95 | 16 | 3.75 | 0.4 | — | — |
| *New Delhi* | | | | | | |
| Av. 1951–52 | 84.3 | 56.6 | 33.5 | 18.7 | 7 | 1.2 |
| 1951 | 86.6 | 55.3 | 33.9 | 20.4 | 6 | 1.3 |
| 1952 | 82.0 | 58.0 | 33.1 | 17.0 | 7.4 | 1.0 |
| *Calcutta* | | | | | | |
| Av. 1951–52 | 57.1 | 21.1 | 9.5 | 2 | 0.01 | — |
| 1951 | 53.9 | 20.3 | 8.4 | 1.3 | — | — |
| 1952 | 60.3 | 22.0 | 10.5 | 2.8 | 0.01 | — |
| *Ahmedabad* | | | | | | |
| 1951 | 85.9 | 28.9 | 19.8 | 5.7 | 0.90 | — |
| *Poona* | | | | | | |
| 1950–1951 | — | 95.0 | 32.0 | 14.4 | 4.0 | 0.6 |
| *Madras* | | | | | | |
| 1953 | 70.2 | 9.6 | — | — | — | — |

# A Note on the Solar Radiation Pattern for the United Arab Republic

By A. F. El Sabban and M. K. Elnesr

Faculty of Science, Cairo University

One of the most important phases of solar energy and its applications is the knowledge of solar radiation reaching the ground.

At Helwan Observatory the solar intensity at normal incidence has been measured on every day with clear skies, for three different altitudes of the sun, using an Angstrom pyrheliometer. A study of the observations taken during the period from February 1914 to December 1923 has been given by Elnesr.[1] These measurements, which are, evidently, of less significance than continuous records under all sorts of weather conditions, were the only possible information on solar energy in the U.A.R. till December 1955, when the Agro-meteorological Station at Giza (30° 2′ N, 31° 13′ E) was equipped with various apparatus recording the total solar radiation (direct plus diffuse) on a horizontal surface. The data obtained are available in full at the station, and Table I provides a monthly comparison of the mean daily values for the three years 1956–58 as given by the Robitzsch actinograph which was installed a few months before the Eppley pyrheliometer and the Kipp solarimeter working presently at the Station.

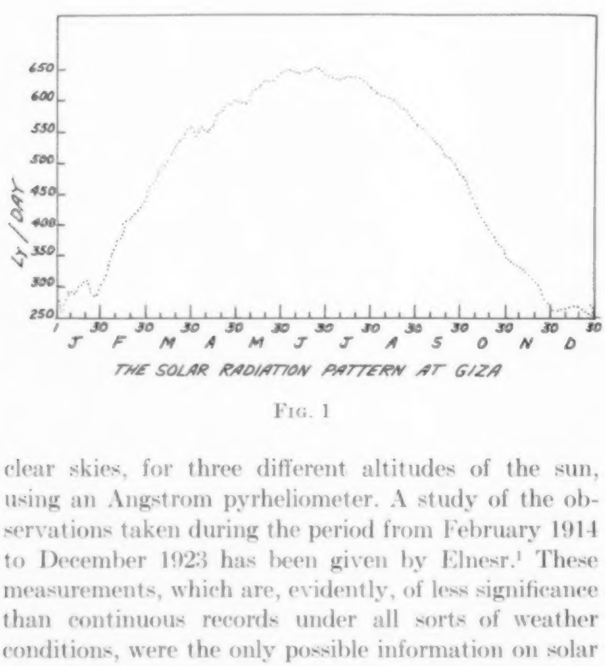



Fig. 1

Such a short period of observations may not be sufficient when dealing with researches concerning solar energy. To obtain representative daily values, ideal for such purposes, a 15 day moving average was applied to the data so as to modify the extreme values without distorting the overall trend of its increase or decrease. The arithmetic mean of the new daily values for the three years was taken and plotted, as shown in Figure 1, giving the solar radiation pattern at Giza.

## REFERENCE

1. Elnesr, M. K., *J. Sci. de la Météorologie*, **32:** 133 (1956).

Table I—Mean daily values of total solar radiation (ly/day) received on a horizontal surface at Giza

| Months | 1956 | 1957 | 1958 | Mean |
|---|---|---|---|---|
| Jan. | 250 | 287 | 276 | 285 |
| Feb. | 375 | 397 | 386 | 386 |
| Mar. | 519 | 493 | 520 | 511 |
| Apr. | 576 | 582 | 576 | 578 |
| May | 643 | 595 | 622 | 626 |
| Jun. | 633 | 672 | 654 | 653 |
| Jul. | 607 | 665 | 643 | 638 |
| Aug. | 566 | 630 | 598 | 598 |
| Sept. | 526 | 547 | 518 | 530 |
| Oct. | 421 | 413 | 411 | 415 |
| Nov. | 306 | 298 | 287 | 300 |
| Dec. | 248 | 282 | 241 | 257 |

# Solar Abstracts

U.S. Air Force Missile Development Center, Holloman Air Force Base, N.M. *Solar furnace support studies. Volume 2.* Prepared by Scientific Consultants to the Office of the Chief Scientist under the direction of Knox Millsaps. Their *Report* AFMDC-TR-59-15; ASTIA Document 213,260, 1959. 303 p. Illus.

A compendium of studies in subjects auxiliary to solar furnace investigations conducted by consultants to the chief scientist during the summer of 1958. Papers are abstracted individually below.

* * *

Brosens, Pierre J. "Aerodynamic stability of a heliostat structure." *Solar furnace support studies, vol. 2.* p. 99–115. Illus.

A rigid, flat mirror structure supported elastically and without damping is studied for stability in the presence of wind. The wind is assumed to have a constant velocity normal to the elevation axis of the mirror. The stability of any translational motion of the mirror, perpendicular to the elevation axis, is then analyzed. It is found that regardless of the intensity of the wind, the mass of the heliostat mirror, and the compliance of its supporting structure, such motions are unstable if, at a given angle of attack, the derivative of the aerodynamic normal force coefficient with respect to the angle of attack is negative. In the case of this mirror, the available data on normal force coefficients is not sufficient to permit drawing a definite conclusion as to whether the present structure is stable or not under the assumed conditions. Should instability obtain, a simple remedy is suggested. (author's abstract)

* * *

—— "Oscillations of a rigid heliostat mirror caused by fluctuating wind." *Ibid.* p. 117–32. Illus.

The response characteristics of an elastically supported rigid heliostat in random vibration are studied. For wind fluctuations of importance, the horizontal and vertical translational motions are uncoupled, and their excitation may be considered separately. Certain assumptions are made pertaining to the random characteristics of the wind, and as a result it is found that the damping required to prevent undesirable oscillations of the heliostat is small and of the order of 1 per cent of critical for both the vertical and horizontal oscillations. (author's abstract)

Foote, J. R.; Adney, J. E., "Some remarks on the design of a solar furnace and the calculation of concentration using spherical-mirror elements." *Ibid.* p. 1–97. Illus.

The problem of replacing a single paraboloidal condenser by an approximate mirror system for a large solar furnace is studied. Ray-tracing methods are outlined for approximate and preliminary studies of various mirror types. For spherical mirrors, having either of the two local principal radii from the paraboloid, formulas are found and methods outlined for calculating the concentration of light at the focal spot. Having selected the qualitatively best array of spherical mirrors, this case is calculated and compared to the performance of the ideal paraboloid. One measure of performance is that the array of spherical mirrors in zones approximately one foot wide gives 97.6 per cent of the performance expected if paraboloidal mirrors could be used. However, no array calculated reaches 700 cal per sq cm per sec over the entire focal spot. (authors' abstract)

* * *

Hughes, Gordon, "A radiation fluxmeter for high intensity applications." *Ibid.* p. 145–59. Illus.

The high energy concentration and the problem of correct flux measurement for a large solar furnace are discussed. The possibility of measuring a known fraction of the total flux to reduce volume of water required is considered. The changes in physical properties of a transparent medium caused by temperature rise are examined as a possible technique. Finally, the sources of error inherent to the instruments are discussed. (author's abstract)

* * *

Jose, Paul D. "The design of a heliostat mirror for a solar furnace." *Ibid.* p. 199–218. Illus.

A general equation is derived from which the shape of the mirror surface for a heliostat may be determined. It is shown that the separation of the heliostat mirror from the collecting area is a critical factor. The two special cases considered illustrate that the shape is dependent on the choice of the axes or rotation of the mirror. The altazimuth type of mount is employed. (author's abstract)

* * *

—— "The design of the condenser of a solar furnace using non-parabolic elements." *Ibid.* p. 219–60. Illus.

For a solar furnace of large dimensions the parabolic condenser may be formed of stressed glass sectors, as in the Trombe furnace, or of preformed mirrors. Although a perfect paraboloid is the best type of concentrating surface for a solar furnace, consideration is given to surfaces which are composed of non-parabolic segments. A condenser composed of spherical mirrors of different radii is found to be unsatisfactory except when the mirrors are quite small. A great number of small mirrors lead to considerable edge loss. Toroidal mirror segments are found to form a satisfactory approach to the paraboloid. All computations are based on front surfaced mirrors, although in practice back surfaced mirrors are more desirable. Perliminary consideration is given to the limb darkening of the sun and the resulting energy distribution in the focal plane. Taking this effect into account, it is found that the flux density is about 10 per cent greater than that given by assuming a solar disk of uniform density.

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—— "The flux through the focal spot of a solar furnace." *Ibid.* p. 261–303. Illus.

The flux distribution through the focal spot of a solar furnace is computed. The discussion assumes a perfect parabolic condenser and takes into account the limb darkening of the sun. The flux density is shown to be greater at the center than at the edge of the focal spot. This difference amounts to about 26 per cent. Throughout the discussion comparisons are made with the work of others who have assumed the sun's disk to be of uniform intensity. (author's abstract)

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Problems of instrumentation for the Cloudcroft solar furnace are considered for the areas of temperature measurement, atmosphere and focal spot aperture control, flux measurement and temperature measurement. Basic considerations of design and development are discussed, and specific recommendations set forth. While little of the necessary instrumentation is commercially available, possible sources are cited for that which can be so obtained. For the remainder, sources for design and development are indicated.

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Several laws of optics assumed without proofs in a previous report dealing with calculations on the solar furnace are proved in detail. They are (1) that the fractional part of the light reflected at each point refraction of a plane parallel glass plate is the same, and (2) that the sum of the fractional part of the light incident on any surface of a plane parallel glass plate reflected therefrom and the fractional part refracted therefrom is equal to unity. Finally, the laws of reflection of a metallic surface with a glass superstrate are deduced. (author's abstract)

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